U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the
ARIZONA DEPARTMENT OF WATER RESOURCES and
BUREAU OF INDIAN AFFAIRS

Ground-Water, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2001–02

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By Blakemore E. Thomas

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Tucson, Arizona
2002

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Cover: Toenleshushe Canyon, Arizona, northern part of study area. Photograph by Don Bills.

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CONVERSION FACTORS AND DATUMS

Multiply	By	To obtain
inch (in)	2.54	centimeter
inch (in)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
acre-foot (acre-ft)	0.001233	cubic hectometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06309	liter per second
gallon per day (gal/d)	0.003785	cubic meter per day

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8°C)+32$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929; horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27). **Altitude**, as used in this report, refers to distance above or below NGVD 29.

ABBREVIATED WATER-QUALITY UNITS

Chemical concentration and water temperature are given only in metric units. Chemical concentration in water is given in milligrams per liter (mg/L) or micrograms per liter (μg/L). Milligrams per liter is a unit expressing the solute mass (milligrams) per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter. For concentrations lower than 7,000 milligrams per liter, the numerical value is about the same as for concentrations in parts per million. Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25°C).

Ground-Water, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2001–02

By Blakemore E. Thomas

Abstract

The N aquifer is the major source of water in the 5,400-square-mile area of Black Mesa in northeastern Arizona. Availability of water is an important issue in this area because of continued industrial and municipal use, a growing population, and precipitation of about 6 to 14 inches per year.

The monitoring program in the Black Mesa area has been operating since 1971 and is designed to determine the long-term effects of ground-water withdrawals from the N aquifer for industrial and municipal uses. The monitoring program includes measurements of (1) ground-water pumping, (2) ground-water levels, (3) spring discharge, (4) surface-water discharge, and (5) ground-water chemistry.

In 2001, total ground-water withdrawals were 7,680 acre-feet, industrial use was 4,530 acre-feet, and municipal use was 3,150 acre-feet. From 2000 to 2001, total withdrawals decreased by 1 percent, industrial use increased by 1 percent, and municipal use decreased by 3 percent.

From 2001 to 2002, water levels declined in 5 of 14 wells in the unconfined part of the aquifer, and the median change was +0.2 foot. Water levels declined in 12 of 17 wells in the confined part of the aquifer, and the median change was -1.4 feet.

From the prestress period (prior to 1965) to 2002, the median water-level change for 32 wells was -15.8 feet. Median water-level changes were -1.3 feet for 15 wells in the unconfined part of the aquifer and -31.7 feet for 17 wells in the confined part.

Discharges were measured once in 2001 and once in 2002 at four springs. Discharges decreased by 26 percent and 66 percent at two springs, increased by 100 percent at one spring, and did not change at one spring. For the past 10 years, discharges from the four springs have fluctuated; however, an increasing or decreasing trend is not apparent.

Continuous records of surface-water discharge have been collected from 1976 to 2001 at Moenkopi Wash, 1996 to 2001 at Laguna Creek, 1993 to 2001 at Dinnebito Wash, and 1994 to 2001 at Polacca Wash. Median flows for November, December, January, and February of each water year were used as an index of ground-water discharge to those streams. Since 1995, the median winter flows have decreased for Moenkopi Wash, Dinnebito Wash, and Polacca Wash. Since 1997, there is no consistent trend in the median winter flow for Laguna Creek.

In 2002, water samples were collected from 12 wells and 4 springs and analyzed for selected chemical constituents. Dissolved-solids concentrations ranged from 96 to 636 milligrams per liter. Water samples from 8 of the wells and from 3 of the springs had less than 300 milligrams per liter of dissolved solids. There are no appreciable time trends in the chemistry of water samples from 9 wells and 4 springs; the 9 wells had more than 7 years of data, and the 4 springs had more than 9 years of data.

INTRODUCTION

The Black Mesa area includes about 5,400 mi^2 in northeastern Arizona (**fig. 1**) and has a diverse topography that includes flat plains, mesas, and incised drainages. Black Mesa is about 2,000 mi^2, is bounded by 2,000-foot cliffs on the north and northeast sides, and slopes gradually downward to the south and southwest. Availability of water is an important issue in the study area because of continued ground-water withdrawals, a growing population, and precipitation that averages about 6 to 14 in. per year (U.S. Department of Agriculture, 1999).

The N aquifer is the major source of water for industrial and municipal uses in the Black Mesa area. The N aquifer consists of three formations—the Navajo Sandstone, the Kayenta Formation, and the Lukachukai Member[1] of the Wingate Sandstone that are hydraulically connected and function as a single aquifer (**fig. 2**). Within the Black Mesa area, Peabody Western Coal Company is the principal industrial user of water, and the Navajo Nation and Hopi Tribe are the principal domestic and municipal users.

Withdrawals from the N aquifer in the Black Mesa area have been increasing during the last 30 years (**table 1**). Peabody Western Coal Company began operating a strip mine in the northern part of the mesa in 1968. The quantity of water pumped by the company increased from about 100 acre-ft in 1968 to a maximum of 4,740 acre-ft in 1982. About 4,530 acre-ft of water was pumped in 2001. Withdrawals for municipal use from the N aquifer have increased steadily from an estimated 250 acre-ft in 1968 to 3,150 acre-ft in 2001.

The Navajo Nation and the Hopi Tribe have been concerned about the long-term effects of withdrawals from the N aquifer on available water supplies, on stream and spring discharge, and on ground-water chemistry. In 1971, these concerns led to the establishment of a monitoring program of the water resources in Black Mesa by the U.S. Geological Survey (USGS) in cooperation with the Arizona Department of Water Resources (ADWR). In 1983, the Bureau of Indian Affairs (BIA) joined the cooperative effort. Since 1983, the Navajo Tribal Utility Authority (NTUA); Peabody Western Coal Company; the Hopi Tribe; and the Western Navajo Agency, Chinle Agency, and Hopi Agency of the BIA have assisted in the collection of hydrologic data.

[1] The name Lukachukai Member was formerly abandoned by Dubiel (1989) and is used herein for report continuity in the monitoring program as it relates to that part of the Wingate Sandstone included in the N aquifer.

Purpose and Scope

This report presents results of ground-water, surface-water, and water-chemistry monitoring in the Black Mesa area from January 2001 to June 2002. The monitoring is designed to determine the effects of industrial and municipal pumpage from the N aquifer on ground-water levels, stream and spring discharge, and ground-water chemistry. Continuous and periodic data are collected for ground water and surface water. Ground-water data include pumpage, water levels, spring discharges, and water chemistry. Surface-water data include discharges at four continuous-record streamflow-gaging stations.

Previous Investigations

Nineteen progress reports on the monitoring program for the Black Mesa area have been prepared by the USGS (U.S. Geological Survey, 1978; G.W. Hill, hydrologist, written commun., 1982, 1983; Hill, 1985; Hill and Whetten, 1986; Hill and Sottilare, 1987; Hart and Sottilare, 1988, 1989; Sottilare, 1992; Littin, 1992, 1993; Littin and Monroe, 1995a, 1995b, 1996, 1997; Littin and others, 1999; Truini and others, 2000; Thomas and Truini, 2000; and Thomas, 2002). Most of the data from the monitoring program are contained in these reports. Stream-discharge and periodic water-quality data from Moenkopi Wash collected before the 1982 water year were published by the U.S. Geological Survey (1963–64a, b; 1965–74a, b; and 1976–83). Stream-discharge data from water years 1983 to 2001 for Moenkopi Wash and other streams in the Black Mesa area are published in White and Garrett (1984, 1986, 1987, and 1988), Wilson and Garrett (1988, 1989), Boner and others (1989, 1990, 1991, 1992), Smith and others (1993, 1994, 1995, 1996, 1997), Tadayon and others (1998, 1999, 2000, 2001), and McCormack and others (2002). Before the monitoring program, a large data-collection effort in the 1950s resulted in a compilation of well and spring data for the Navajo and Hopi Indian Reservations (Davis and others, 1963).

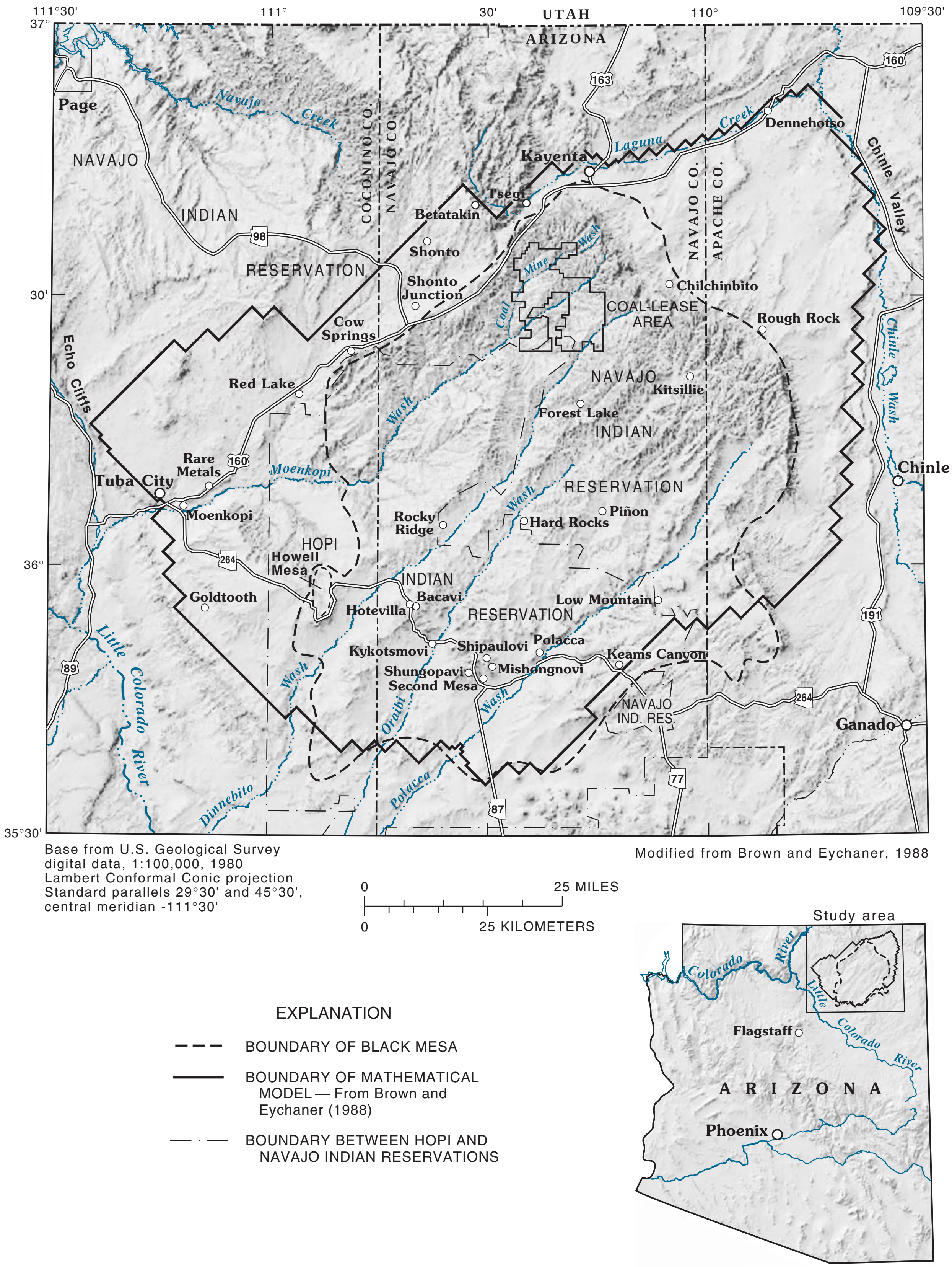


Figure 1. Location of study area.

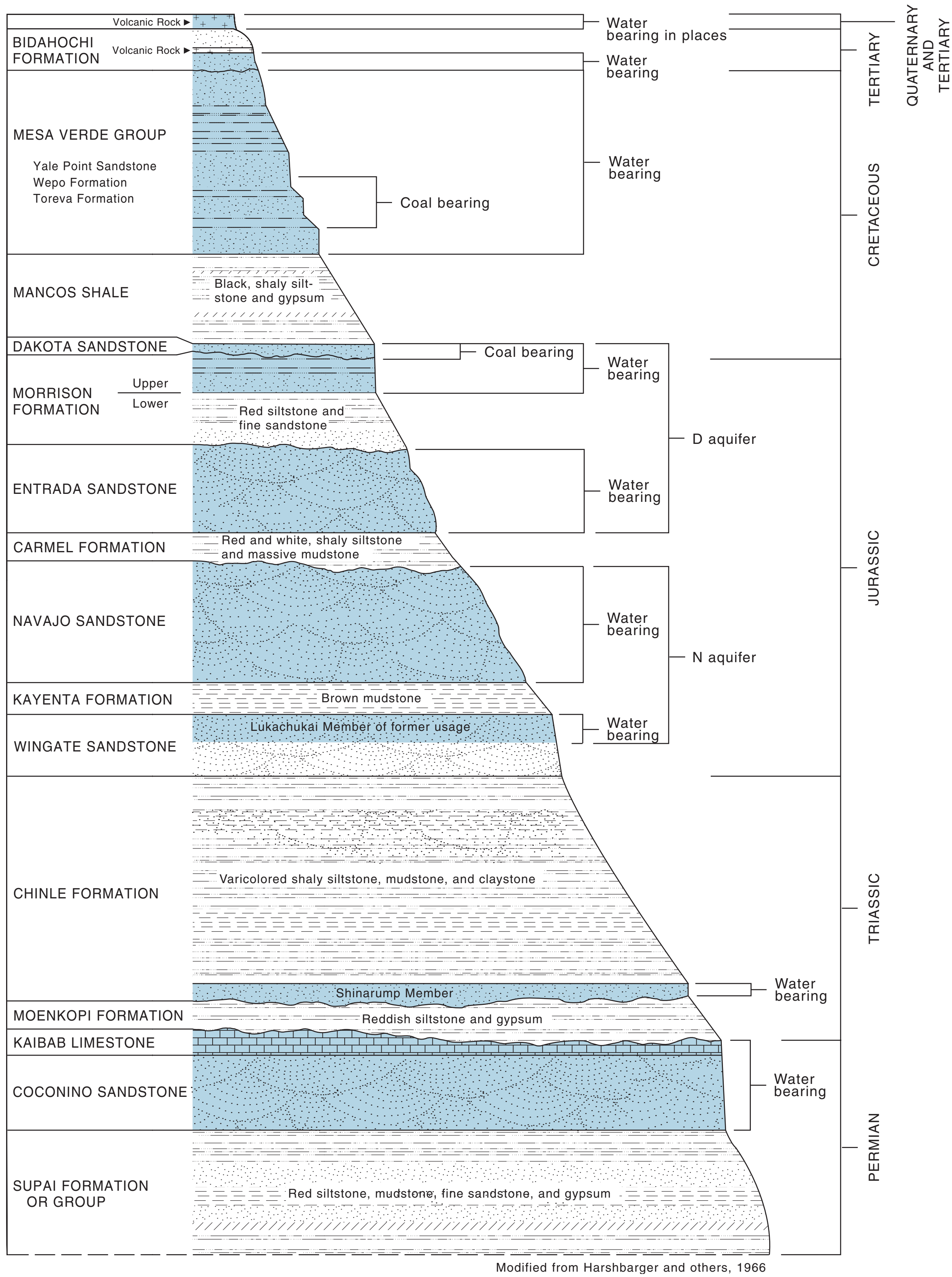


Figure 2. Rock formations and hydrogeologic units of the Black Mesa area, Arizona (not to scale). The N aquifer is approximately 1,000 ft thick.

Table 1. Withdrawals from the N aquifer, Black Mesa area, Arizona, 1965–2001

[Values are rounded to nearest 10 acre-feet. Data for 1965–79 from Eychaner (1983). Total withdrawals in Littin and Monroe (1996) were for the confined part of the aquifer]

Year	Industrial[1]	Municipal[2,3]		Total withdrawals	Year	Industrial[1]	Municipal[2,3]		Total withdrawals
		Confined	Unconfined				Confined	Unconfined	
1965	0	50	20	70	1984	4,170	1,070	1,400	6,640
1966	0	110	30	140	1985	2,520	1,040	1,160	4,720
1967	0	120	50	170	1986	4,480	970	1,260	6,710
1968	100	150	100	350	1987	3,830	1,130	1,280	6,240
1969	40	200	100	340	1988	4,090	1,250	1,310	6,650
1970	740	280	150	1,170	1989	3,450	1,070	1,400	5,920
1971	1,900	340	150	2,390	1990	3,430	1,170	1,210	5,810
1972	3,680	370	250	4,300	1991	4,020	1,140	1,300	6,460
1973	3,520	530	300	4,350	1992	3,820	1,180	1,410	6,410
1974	3,830	580	360	4,770	1993	3,700	1,250	1,570	6,520
1975	3,500	600	510	4,610	1994	4,080	1,210	1,600	6,890
1976	4,180	690	640	5,510	1995	4,340	1,220	1,510	7,070
1977	4,090	750	730	5,570	1996	4,010	1,380	1,650	7,040
1978	3,000	830	930	4,760	1997	4,130	1,380	1,580	7,090
1979	3,500	860	930	5,290	1998	4,030	1,440	1,590	7,060
1980	3,540	910	880	5,330	1999	4,210	1,420	1,480	7,110
1981	4,010	960	1,000	5,970	2000	4,490	1,610	1,640	7,740
1982	4,740	870	960	6,570	2001	4,530	1,490	1,660	7,680
1983	4,460	1,360	1,280	7,100					

[1]Metered pumpage from the confined part of the aquifer by Peabody Western Coal Company.

[2]Does not include withdrawals from the wells equipped with windmills.

[3]Includes estimated pumpage, 1965–73, and metered pumpage, 1974–79, at Tuba City; metered pumpage at Kayenta and estimated pumpage at Chilchinbito, Rough Rock, Piñon, Keams Canyon, and Kykotsmovi before 1980; metered and estimated pumpage furnished by the Navajo Tribal Utility Authority and the Bureau of Indian Affairs and collected by the U.S. Geological Survey, 1980–85; and metered pumpage furnished by the Navajo Tribal Utility Authority, the Bureau of Indian Affairs, various Hopi Village Administrations, and the U.S. Geological Survey, 1986–2000.

Many interpretive studies have been done in the Black Mesa area. Cooley and others (1969) made the first comprehensive evaluation of the regional hydrogeology of the Black Mesa area. Eychaner (1983) developed a two-dimensional numerical model of ground-water flow in the N aquifer. Brown and Eychaner (1988) recalibrated the model using a finer grid and revised estimates of selected aquifer characteristics. GeoTrans, Inc. (1987) also developed a two-dimensional model of the N aquifer in the 1980s. In the late 1990s, HSIGeoTrans, Inc. and Waterstone Environmental Hydrology and Engineering, Inc. (1999) developed a detailed three-dimensional numerical model of the D and N aquifers.

Kister and Hatchett (1963) made the first comprehensive evaluation of the chemistry of water from wells and springs in the Black Mesa area. HSIGeoTrans, Inc. (1993) evaluated the major-ion and isotopic chemistry of the D and N aquifers. Lopes and Hoffmann (1997) analyzed ground-water ages, recharge, and hydraulic conductivity of the N aquifer using geochemical techniques. Zhu and others (1998) estimated ground-water recharge using isotopic data and flow estimates from the model developed by GeoTrans, Inc. (1987). Zhu (2000) estimated recharge again using the same isotopic data, but added numerical flow and transport modeling to the method.

HYDROLOGIC DATA

In 2001–02, the Black Mesa monitoring program included metering and estimating ground-water withdrawals, measuring depth to ground water, measuring discharge in streams and springs, and collecting and analyzing water samples from wells and springs. Continuous monitoring was done on ground-water withdrawals from 34 well systems, water levels at 6 observation wells, and surface-water discharge at 4 sites. Annual measurements were made of discharge at 4 springs and ground-water levels at 27 wells. Spring discharges and ground-water levels were measured between April and June 2002. Ground-water samples were collected from 12 wells and 4 springs in April–June 2002 and analyzed for chemical constituents. Identification information for the 49 wells used for water-level measurements and water-quality sampling is shown in table 2.

Table 2. Identification numbers and names of study wells, Black Mesa area, Arizona

[Dashes indicate no data.]

U.S. Geological Survey identification number	Common name or location	Bureau of Indian Affairs site number	U.S. Geological Survey identification number	Common name or location	Bureau of Indian Affairs site number
354749110300101	Second Mesa PM2	---	362149109463301	Rough Rock	10R-111
355023110182701	Keams Canyon PM2	---	362333110250001	Peabody 9	---
355034110183001	Keams Canyon PM3	---	362406110563201	White Mesa Arch	1K-214
355215110375001	Kykotsmovi PM2	---	362418109514601	Rough Rock PM5	---
355230110365801	Kykotsmovi PM1	---	362456110503001	Cow Springs	1K-225
355236110364501	Kykotsmovi PM3	---	362647110243501	Peabody 4	---
355428111084601	Goldtooth	3A-28	362823109463101	Rough Rock	10R-119
355518110400301	Hotevilla PM1	---	362936109564101	BM observation well 1	8T-537
355638110060401	Low Mountain PM2	---	363013109584901	Sweetwater Mesa	8K-443
355648110475501	Howell Mesa	6H-55	363103109445201	Rough Rock	9Y-95
355924110485001	Howell Mesa	3K-311	363137110044702	Chilchinbito PM3	---
360055110304001	BM observation well 5	4T-519	363143110355001	BM observation well 4	2T-514
360217111122601	Tuba City	3K-325	363213110342001	Shonto Southeast	2K-301
360418110352701	Rocky Ridge PM2	---	363232109465601	Rough Rock	9Y-92
360527110122501	Piñon NTUA 1	---	363309110420501	Shonto	2K-300
360614110130801	Piñon PM6	---	363423110305501	Shonto Southeast	2T-502
360734111144801	Tuba City	3T-333	363558110392501	Shonto PM2	---
360904111140201	Tuba City NTUA 1	3T-508	363727110274501	Long House Valley	8T-510
360918111080701	Tuba City Rare Metals 2	---	363850110100801	BM observation well 2	8T-538
360924111142201	Tuba City NTUA 3	---	364034110240001	Marsh Pass	8T-522
360953111142401	Tuba City NTUA 4	3T-546	364226110171701	Kayenta West	8T-541
361225110240701	BM observation well 6	---	364248109514601	Northeast Rough Rock	8A-180
361737110180301	Forest Lake NTUA 1	4T-523	364338110154601	BM observation well 3	8T-500
361832109462701	Rough Rock	10T-258	364344110151201	Kayenta PM2	8A-295
362043110030501	Kitsillie NTUA 2	---			

Withdrawals from the N Aquifer

Withdrawals from the N aquifer are separated into three categories—(1) industrial use from the confined part of the aquifer, (2) municipal use from the confined part of the aquifer, and (3) municipal use from the unconfined part of the aquifer (**table 1**, fig. 3). The industrial category includes eight wells at the well field of Peabody Western Coal Company in northern Black Mesa (**fig. 4**). The BIA, NTUA, and Hopi Tribe operate about 70 municipal wells (fig. 4). Withdrawals from the N aquifer were compiled primarily on the basis of metered data (tables 1 and 3).

Withdrawals from wells equipped with windmills are not measured in this monitoring program. About 270 windmills in the Black Mesa area withdraw water from the D and N aquifers, and estimated total withdrawals by the windmills are about 65 acre-ft/yr (HSIGeoTrans, Inc., and Waterstone Environmental Hydrology and Engineering, Inc., 1999). This amount is less than 1 percent of the total annual withdrawal from the N aquifer.

In 2001, the total ground-water withdrawal from the N aquifer was about 7,680 acre-ft (table 1), which is a 1 percent decrease from the total withdrawal in 2000. Withdrawals for municipal use from the confined part of the aquifer totaled 1,490 acre-ft, which is a 7 percent decrease from 2000. Withdrawals for municipal use from the unconfined part of the aquifer totaled 1,660 acre-ft, which is a 1 percent increase. Withdrawals for industrial use totaled 4,530 acre-ft, which is a 1 percent increase.

Withdrawals from the N aquifer have been increasing since the 1970s (table 1, fig. 3). Total withdrawals increased from 1,170 acre-ft in 1970 to 4,300 acre-ft in 1972 when industrial use increased from 740 to 3,680 acre-ft. Since 1973, industrial use has fluctuated between 2,520 and 4,740 acre-ft/yr. Municipal use increased by about 20 percent per year during the 1970s, slowed to an increase of about 4 percent per year in the 1980s, and slowed further to an increase of about 3 percent per year in the 1990s.

In the 1970s, industrial use was about 75 percent of the total withdrawal. With the increase in municipal use over the last 30 years, industrial use, as a percentage of total withdrawals, has declined to about 60 percent in the late 1990s and in 2001.

In an effort to improve and ensure the accuracy of ground-water withdrawal data, a quality-assurance program was begun in 1985 for withdrawal data from industrial and municipal wells completed in the N aquifer. Nearly all industrial and municipal wells in the study area are equipped with totalizing flowmeters to measure ground-water withdrawals. The flowmeters on the wells are tested about once every 5 years by measuring pumpage with a calibrated mechanical flowmeter and comparing the measured pumpage to the metered pumpage. For the purpose of this study, the allowable difference between the discharge measured by the permanent totalizing flowmeter and the test meter is 10 percent. No testing of flowmeters was done this past year.

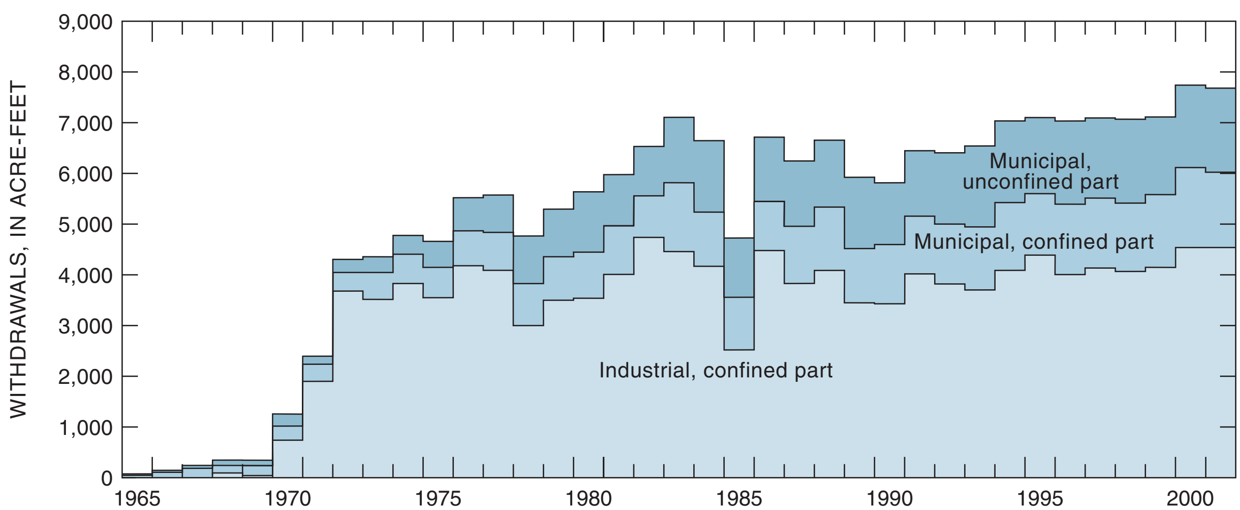


Figure 3. Withdrawals from the N aquifer, Black Mesa area, Arizona, 1965–2001.

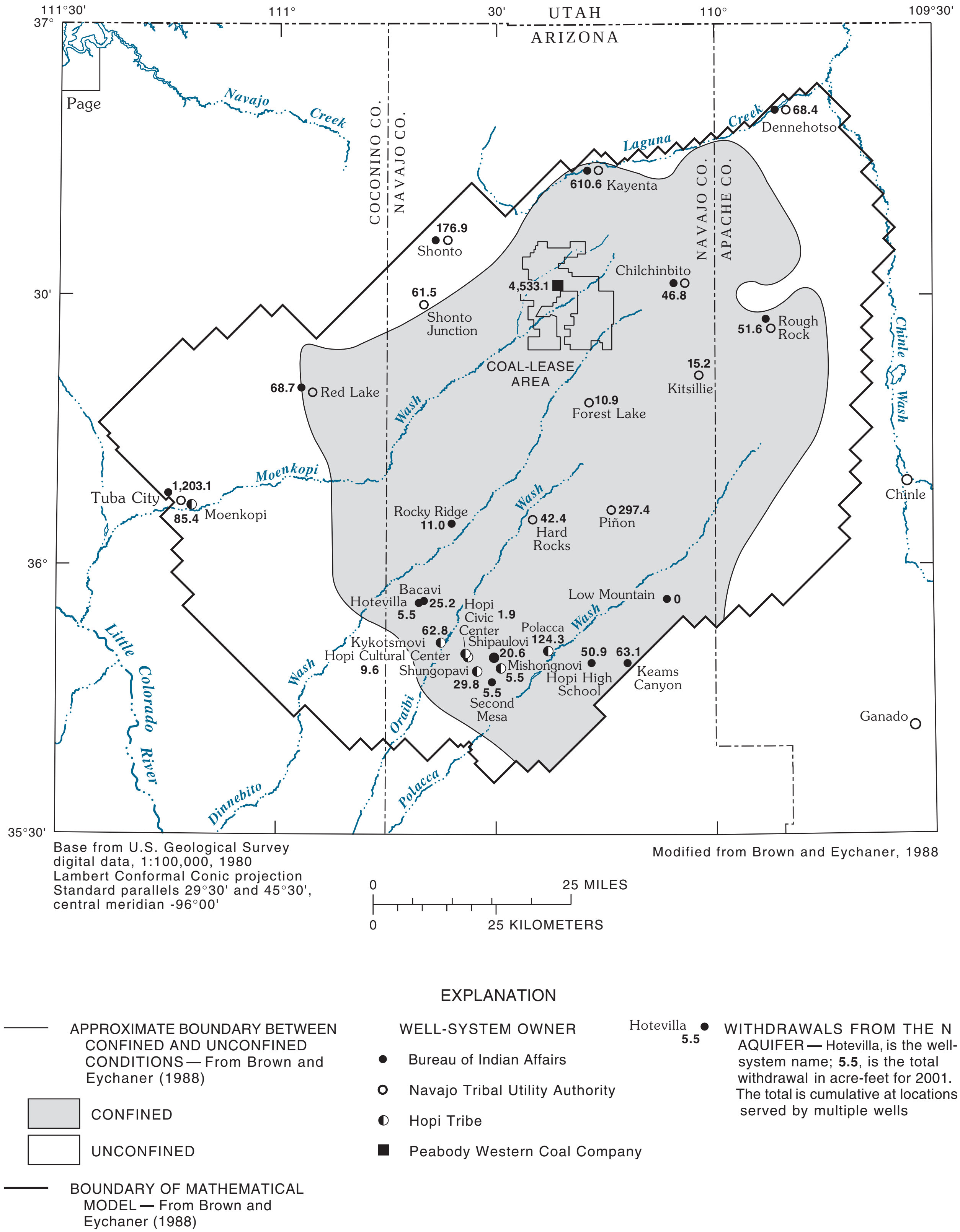


Figure 4. Locations of well systems monitored for withdrawals from the N aquifer, Black Mesa area, Arizona, 2001.

Table 3. Withdrawals from the N aquifer by well system, Black Mesa area, Arizona, 2001

[Withdrawals, in acre-feet, are from flowmeter measurements. BIA, Bureau of Indian Affairs; NTUA, Navajo Tribal Utility Authority; USGS, U.S. Geological Survey; Peabody, Peabody Western Coal Company; Hopi, Hopi Village Administrations]

Well system (one or more wells)	Owner	Source of data	Withdrawals: Confined aquifer	Withdrawals: Unconfined aquifer
Chilchinbito	BIA	USGS/BIA	6.5	
Dennehotso	BIA	USGS/BIA		29.0
Hopi High School	BIA	USGS/BIA	50.9	
Hotevilla	BIA	USGS/BIA	5.5	
Kayenta	BIA	USGS/BIA	67.8	
Keams Canyon	BIA	USGS/BIA	63.1	
Low Mountain	BIA	USGS/BIA	[1]0.0	
Piñon	BIA	USGS/BIA	[1]0.0	
Red Lake	BIA	USGS/BIA		6.3
Rocky Ridge	BIA	USGS/BIA	11.0	
Rough Rock	BIA	USGS/BIA	34.6	
Second Mesa	BIA	USGS/BIA	5.5	
Shonto	BIA	USGS/BIA		158.8
Tuba City	BIA	USGS/BIA		154.2
Chilchinbito	NTUA	NTUA	40.3	
Dennehotso	NTUA	NTUA		39.4
Forest Lake	NTUA	NTUA	10.9	
Hard Rock	NTUA	NTUA	42.4	
Kayenta	NTUA	NTUA	542.8	
Kitsillie	NTUA	NTUA	15.2	
Piñon	NTUA	NTUA	297.4	
Red Lake	NTUA	NTUA		62.4
Rough Rock	NTUA	NTUA	17.0	
Shonto	NTUA	NTUA		18.1
Shonto Junction	NTUA	NTUA		61.5
Tuba City	NTUA	NTUA		1,048.9
Mine Well Field	Peabody	Peabody	[2]4,533.1	
Bacavi	Hopi	USGS/Hopi	25.2	
Hopi Civic Center	Hopi	USGS/Hopi	1.9	
Hopi Cultural Center	Hopi	USGS/Hopi	9.6	
Kykotsmovi	Hopi	USGS/Hopi	62.8	
Mishongnovi	Hopi	USGS/Hopi	5.5	
Moenkopi	Hopi	USGS/Hopi		85.4
Polacca	Hopi	USGS/Hopi	[3]124.3	
Shipaulovi	Hopi	USGS/Hopi	20.6	
Shungopovi	Hopi	USGS/Hopi	29.8	

[1] Well taken out of service.
[2] Industrial pumpage.
[3] Estimated. Well PM4 not metered. Annual pumpage from PM4 was estimated as 37.0 acre-feet on the basis of previous metered data and an estimated 33,000 gallons per day. Pumping from the remaining wells (PM5 and PM6) may include some water from the D aquifer.

Ground-Water Levels in the N Aquifer

Ground water in the N aquifer is under confined conditions in the central part of the study area and under unconfined or water-table conditions around the periphery (**fig. 5**). The ground water generally flows radially outward from recharge areas near Shonto to the southwest, south, southeast, and east (Thomas, 2002).

Ground-water levels are measured each year and compared with levels from previous years to determine changes over time. In April–June 2002, water levels were measured in 32 wells that are used for observation, municipal supply, or stock supply (**table 4**). Six of the 32 wells are observation wells that were operated on a continuous basis; water levels were recorded daily. Water levels were measured manually four times between April 2001 and April 2002 in the six continuous-observation wells.

The wells used for water-level measurements are spread throughout the study area (fig. 5). Although all the wells are completed in the N aquifer, characteristics of the wells vary considerably. Construction dates range from 1934 to 1993, depths range from 107 to 3,535 ft, and depths to the top of the N aquifer range from 0 to 2,400 ft (**table 5**).

From 2001 to 2002, water levels declined in 17 of 31 wells. The median water-level change in the 31 wells was -0.2 ft. Changes ranged from -22.7 ft in the Keams Canyon PM2 well to +7.7 ft in well 2T-502 (table 4).

From 2001 to 2002, water levels declined in 5 of 14 wells in unconfined areas. The median change was +0.2 ft, and the changes ranged from -3.4 ft to +7.7 ft. In confined areas, water levels declined in 12 of 17 wells. The median change was -1.4 ft, and the changes ranged from -22.7 ft to +6.1 ft (table 4).

Median annual water-level changes for observation wells from 1983 to 2002 are shown in **figure 6**. Median annual changes before 1983 are not shown because there were insufficient water-level data to compute median values. For wells in confined areas, the average annual median water-level change was -1.8 ft, and there is no appreciable trend in the annual water-level changes from 1983 to 2002. For wells in unconfined areas, the average annual median water-level change was +0.2 ft, and there is a break in the trend of annual water-level changes. There is no appreciable trend from 1983 to 1992, and there is a decreasing trend from 1993 to 2001.

From the prestress period (prior to 1965) to 2002, the median water-level change in 32 wells was -15.8 ft. Water levels in 15 unconfined wells had a median change of -1.3 ft and ranged from -42 ft to +14.6 ft (table 4). Water levels in 17 confined wells had a median change of -31.7 ft and ranged from -191.5 ft to +15.5 ft.

The areal distribution of water-level changes from the prestress period to 2002 is shown in figure 5. Hydrographs of water levels in the annual observation-well network show the time trends of changes since the 1950s, 1960s, or 1970s (**fig. 7**). In most of the unconfined area, water levels have changed only slightly. In the Tuba City area, however, water levels have declined 30 to 40 ft in a few of the wells. In most of the confined area, water levels have declined; however, the magnitudes of declines are variable. Larger declines are near the municipal pumping centers (wells Piñon PM6 and Keams Canyon PM2) or near the wells for Peabody Western Coal Company. Smaller declines are away from the pumping centers (wells 8T-522 and 10R-119).

Hydrographs for the Black Mesa observation wells show continuous water-level changes since about 1972 (**fig. 8**). Water levels in the two wells in unconfined areas (BM1 and BM4) have had small seasonal or year-to-year variation and have had small long-term changes since 1972. Water levels in the four wells in confined areas also have had little seasonal variation (except BM3); however, the water levels have consistently declined in all the confined wells since 1972.

Spring Discharge from the N Aquifer

Ground water in the N aquifer discharges from many springs around the margins of the Black Mesa area. Discharge from selected springs is measured annually and compared to discharge from previous years to determine changes in spring discharge over time. In April–July 2002, discharge was measured at four springs (**table 6**). Three springs are on the west or southwest side of the Black Mesa area, and one is on the northeast side (**fig. 9**). The discharge measured at all four springs represents only part of the total discharge from each spring. Because of separate seeps and problematic measuring conditions, it would be difficult to measure the total discharge at those sites.

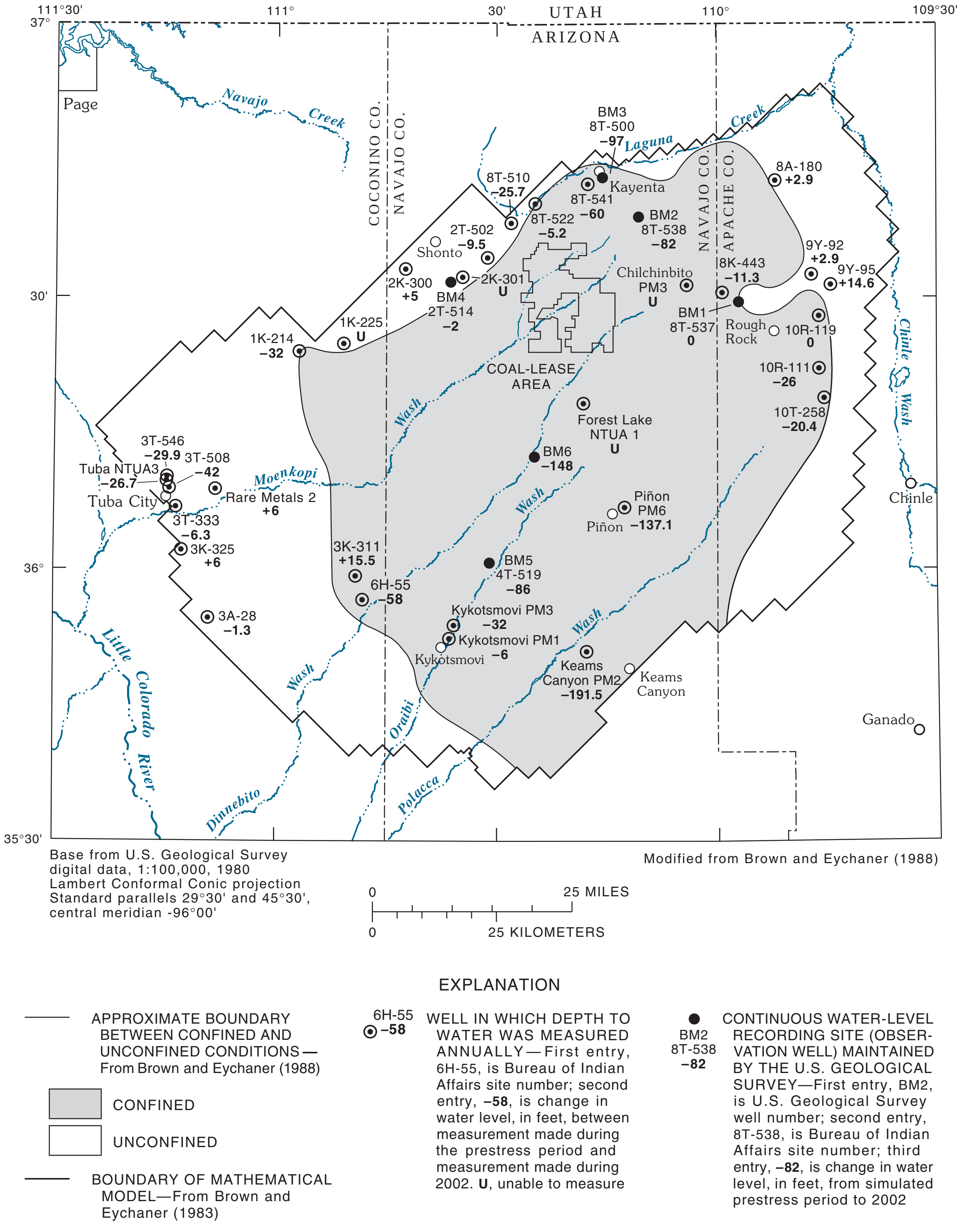


Figure 5. Water-level changes in N aquifer wells from the prestress period to 2002, Black Mesa area, Arizona.

Table 4. Water-level changes in wells completed in the N aquifer, Black Mesa area, Arizona, prestress period to 2002

[Dashes indicate no data. Do., ditto; R, reported from driller's log]

Common name or location	Bureau of Indian Affairs site number	Change in water level from preceding year, in feet: 2001	Change in water level from preceding year, in feet: 2002	Water level, in feet below land surface, 2002[1]	Prestress period water level[2]: Feet below land surface	Prestress period water level[2]: Date	Change in water level from prestress period to 2002, in feet
Unconfined area							
BM observation well 1[3]	8T-537	-0.3	+0.2	374.3	374	([3])	0
BM observation well 4[3]	2T-514	+0.4	-1.3	218.2	[4]216	([3])	-2
Cow Springs	1K-225	([5])	([5])	([5])	60	07–04–54	([5])
Goldtooth	3A-28	[6]-.5	-0.1	231.3	230.0	10–29–53	-1.3
Long House Valley	8T-510	-0.7	-1.5	125.1	99.4	08–22–67	-25.7
Northeast Rough Rock	8A-180	-0.5	+0.4	44.0	46.9	11–13–53	+2.9
Rough Rock	9Y-95	([7])	([7])	104.9	119.5	08–03–49	+14.6
Do	9Y-92	-0.4	-0.2	165.9	168.8	12–13–52	+2.9
Shonto	2K-300	+0.4	+0.4	171.5	176.5	06–13–50	+5.0
Shonto Southeast	2K-301	-0.3	([8])	([8])	283.9	12–10–52	([8])
Do	2T-502	-7.6	+7.7	415.3	405.8	08–22–67	-9.5
Tuba City	3T-333	+2.3	+0.4	29.3	23.0	12–02–55	-6.3
Do	3K-325	+0.3	+0.1	201.6	208	06–30–55	+6
Tuba City Rare Metals 2	---	+0.8	+0.3	51.5	57	09–24–55	+6
Tuba NTUA 1	3T-508	-0.6	-3.4	71.2	29	02–12–69	-42
Tuba NTUA 3	---	-1.0	+0.2	60.9	34.2	11–08–71	-26.7
Tuba NTUA 4	3T-546	-3.4	+0.5	63.6	33.7	08–06–71	-29.9
Confined area							
BM observation well 2[3]	8T-538	-2.9	-2.1	206.5	125	([3])	-82
BM observation well 3[3]	8T-500	-7.0	-0.5	152.0	[4]55.0	04–29–63	-97.0
BM observation well 5[3]	4T-519	-1.9	-3.7	409.7	324	([3])	-86
BM observation well 6[3]	---	-4.4	-6.9	844.9	[4]697	([3])	-148
Chilchinbito PM3	---	-0.5	([5])	([5])	405.3	09–25–65	([5])
Forest Lake NTUA 1	4T-523	([5])	([5])	([5])	1,096R	05–21–82	([5])
Howell Mesa	3K-311	([9])	+6.1	447.5	463.0	11–03–53	+15.5
Howell Mesa	6H-55	+0.2	-0.3	270.3	212	07–08–54	-58
Kayenta West	8T-541	-4.1	+1.0	289.5	230	03–17–76	-60
Keams Canyon PM2	---	+6.0	-22.7	484.0	292.5	06–10–70	-191.5
Kykotsmovi PM1	---	+2.3	+4.5	226.1	220	05–20–67	-6
Kykotsmovi PM3	---	([9])	-1.6	241.7	210	08–28–68	-32
Marsh Pass	8T-522	-1.7	0.0	130.7	125.5	02–07–72	-5.2
Piñon PM6	---	-10.8	-7.1	880.7	743.6	05–28–70	-137.1

Table 4. Water-level changes in wells completed in the N aquifer, Black Mesa area, Arizona, prestress period to 2002—Continued

Common name or location	Bureau of Indian Affairs site number	Change in water level from preceding year, in feet		Water level, in feet below land surface, 2002[1]	Prestress period water level[2]		Change in water level from prestress period to 2002, in feet
		2001	2002		Feet below land surface	Date	
Confined area—Continued							
Rough Rock	10R-119	+0.8	-1.4	256.6	256.6	12–02–53	0.0
Do	10T-258	+0.3	-12.4	321.4	301.0	04–14–60	-20.4
Do	10R-111	+1.3	-2.4	196.1	170	08–04–54	-26
Sweetwater Mesa	8K-443	+0.3	-1.0	540.7	529.4	09–26–67	-11.3
White Mesa Arch	1K-214	+0.6	+0.5	219.5	188	06–04–53	-32

[1]Water level measured during April to June 2002.

[2]Prestress refers to the period of record before appreciable ground-water withdrawals for mining or municipal purposes—about 1965. For wells that had no water-level measurement before 1965, the earliest water-level measurement is shown.

[3]Continuous recorder. Except for well BM3, prestress water levels were estimated from a ground-water model (Brown and Eychaner, 1988).

[4]Prestress water levels for indicated wells were changed from previous Black Mesa monitoring reports to more accurately represent prestress conditions. The water level in BM3 was 77.1 feet in the 1998 report and 60 feet in the 1995–97 reports. The water levels were 217 feet in BM4 and 735.6 feet in BM6 in the 1995–98 reports.

[5]Water level not measured because of obstruction in well, no access to well, or not visited.

[6]Change in water level from last measurement 2 to 4 years earlier.

[7]2001 water level influenced by pumping.

[8]2002 water level influenced by pumping.

[9]Change in water level not shown because last measurement was more than 4 years ago.

Table 5. Well-construction characteristics, depth to top of N aquifer, and type of data collected for wells in monitoring program, Black Mesa area, Arizona, 2001–02

Bureau of Indian Affairs site number, or common name	Date well was completed	Land- surface elevation, in feet	Well depth, in feet below land surface	Screened/open interval(s), in feet below land surface	Depth to top of N aquifer, in feet below land surface[1]	Type of data collected
8T-537 (BM observation well 1)	02–01–72	5,864	850	300–360;400–420; 500–520;600–620; 730–780	290	Water level
8T-538 (BM observation well 2)	01–29–72	5,656	1,338	470–1,338	452	Water level
8T-500 (BM observation well 3)	07–29–59	5,724	868	712–868	155	Water level
2T-514 (BM observation well 4)	02–15–72	6,320	400	250–400	160	Water level
4T-519 (BM observation well 5)	02–25–72	5,869	1,683	1,521–1,683	1,520	Water level
BM observation well 6	01–31–77	6,332	2,507	1,954–2,506	1,950	Water level
1K-214	05–26–50	5,771	356	168–356	250	Water level
1K-225	07–04–54	5,722	251	19–251	[2]10	Water level
2K-300	[3]06–00–50	6,264	300	260–300	0	Water level

See footnotes at end of table.

Table 5. Well-construction characteristics, depth to top of N aquifer, and type of data collected for wells in monitoring program, Black Mesa area, Arizona, 2001–02—Continued

Bureau of Indian Affairs site number, or common name	Date well was completed	Land- surface elevation, in feet	Well depth, in feet below land surface	Screened/open interval(s), in feet below land surface	Depth to top of N aquifer, in feet below land surface[1]	Type of data collected
2K-301	06–12–50	6,435	500	318–328; 378–500	[2]30	Water level
2T-502	08–10–59	6,670	523	12–523	[2]5	Water level
3A-28	04–19–35	5,381	358	([4])	60	Water level
3K-311	[3]11–00–34	5,855	745	380–395 605–745	615	Water level
3K-325	06–01–55	5,250	450	75-450	[2]30	Water level
3T-333	12–02–55	4,940	229	63–229	[2]4	Water level
3T-508 (Tuba City NTUA 1)	08–25–59	5,119	475	([4])	0	Water level, withdrawals
3T-546 (Tuba City NTUA 4)	[3]08–00–71	5,206	612	256–556	0	Water level, withdrawals
4T-523 (Forest Lake NTUA 1)	10–01–80	6,654	2,674	1,870–1,910 2,070–2,210 2,250–2,674	([5])	Water level, water chemistry, withdrawals
6H-55	12–08–44	5,635	361	310–335	310	Water level
8A-180	01–20–39	5,200	107	60–107	[2]40	Water level
8A-295 (Kayenta PM2)	[3]00–00–36	5,623	840	268–280 691–788	95	Water chemistry, withdrawals
8K-443	08–15–57	6,024	720	619–720	590	Water level
8T-510	02–11–63	6,262	314	130–314	[2]125	Water level
8T-522	[3]07–00–63	6,040	933	180–933	480	Water level
8T-541	03–17–76	5,885	890	740–890	700	Water level
9Y-92	01–02–39	5,615	300	154–300	[2]50	Water level
9Y-95	11–05–37	5,633	300	145–300	[2]68	Water level
10R-111	04–11–35	5,757	360	267–360	210	Water level
10R-119	01–09–35	5,775	360	(4)	310	Water level
10T-258	04–12–60	5,903	670	465–670	460	Water level
Chilchinbito PM3	09–25–65	5,950	1,600	1,140–1,570	1,136	Withdrawals
Hotevilla PM1	[3]06–00–57	6,357	1,757	1,500–1,750	1,450	Water chemistry withdrawals
Keams Canyon PM2	[3]05–00–70	5,809	1,106	906–1,106	900	Water level, withdrawals
Keams Canyon PM3	[3]01–00–76	5,806	1,090	931–1,090	930	Water chemistry
Kitsillie NTUA 2	11–09–93	6,780	2,620	2,217–2,223 2,240–2,256 2,314–2,324 2,344–2,394 2,472–2,527	2,205	Water chemistry, withdrawals
Kykotsmovi PM1	02–20–67	5,657	995	655–675 890–990	880	Water level, withdrawals
Kykotsmovi PM2	10–14–77	5,717	1,160	950–1,160	890	Water chemistry, withdrawals

See footnotes at end of table.

Table 5. Well-construction characteristics, depth to top of N aquifer, and type of data collected for wells in monitoring program, Black Mesa area, Arizona, 2001–02—Continued

Bureau of Indian Affairs site number, or common name	Date well was completed	Land- surface elevation, in feet	Well depth, in feet below land surface	Screened/open interval(s), in feet below land surface	Depth to top of N aquifer, in feet below land surface[1]	Type of data collected
Kykotsmovi PM3	08–07–68	5,618	1,220	850–1,220	840	Water level, withdrawals
Low Mountain PM2	[3]04–00–72	6,123	1,343	1,181–1,262	1,153	Water level
Peabody 4	[3]05–00–68	6,229	3,535	2,029–3,458	2,280	Water chemistry, withdrawals
Peabody 9	[3]00–00–83	6,385	3,510	2,332–3,505	2,400	Water chemistry, withdrawals
Piñon NTUA 1	02–25–80	6,336	2,350	1,860–2,350	1,850	Water chemistry withdrawals
Piñon PM6	[3]02–00–70	6,397	2,248	1,895–2,243	1,870	Water level, withdrawals
Rocky Ridge PM2	06–26–63	5,985	1,780	1,480–1,780	1,442	Water level
Rough Rock PM5	06–27–64	6,299	1,420	1,180–1,420	1,156	Water chemistry, withdrawals
Second Mesa PM2	[3]10–00–68	5,777	1,090	740–1,090	720	Water chemistry, withdrawals
Shonto PM2	05–05–61	6,465	554	485–510	0	Water chemistry
Tuba City NTUA 3	[3]10–00–71	5,176	442	142–442	34	Water level, withdrawals
Tuba City Rare Metals 2	[3]09–00–55	5,108	705	100–705	[2]55	Water level

[1]Depth to top of N aquifer from Eychaner (1983) and Brown and Eychaner (1988).
[2]All material between land surface and top of the N aquifer is unconsolidated—soil, alluvium, or dune sand.
[3]00, indicates month or day is unknown.
[4]Screened and (or) open intervals are unknown.
[5]Depth to top of N aquifer was not estimated.

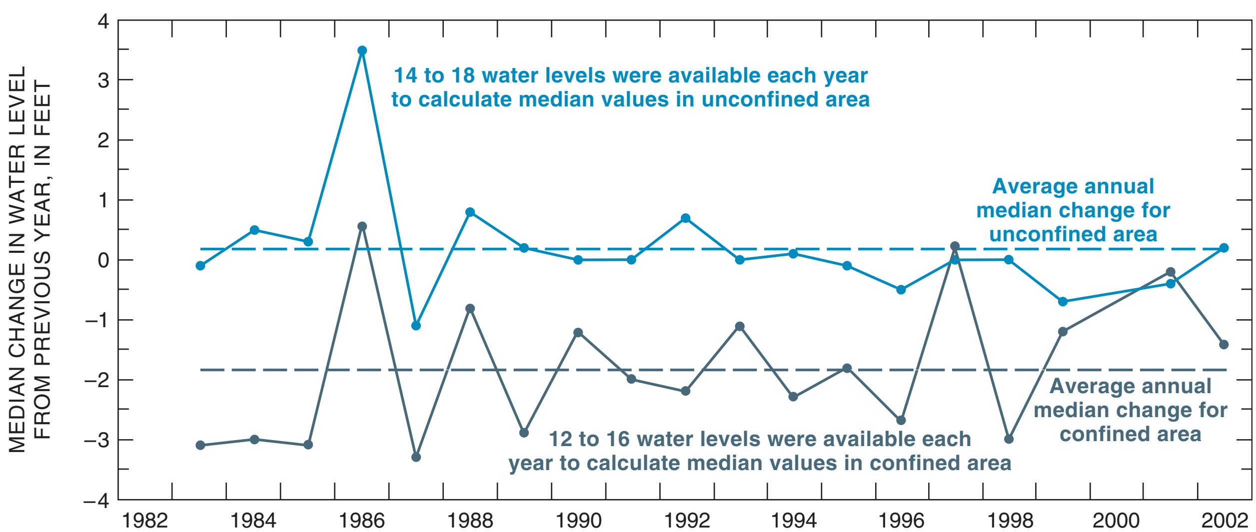


Figure 6. Annual water-level changes for observation wells completed in the N aquifer, Black Mesa area, Arizona, 1983–2002.

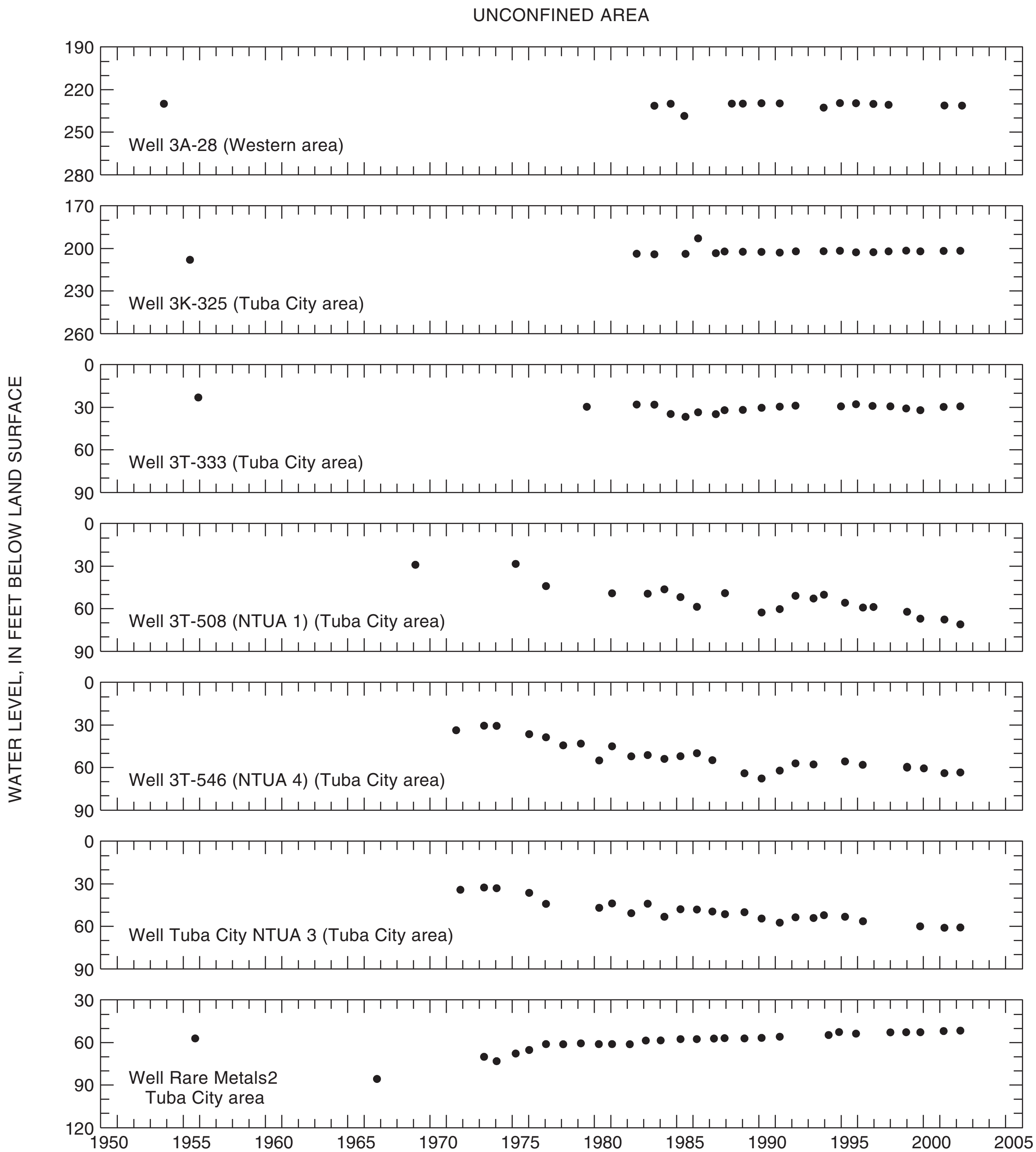
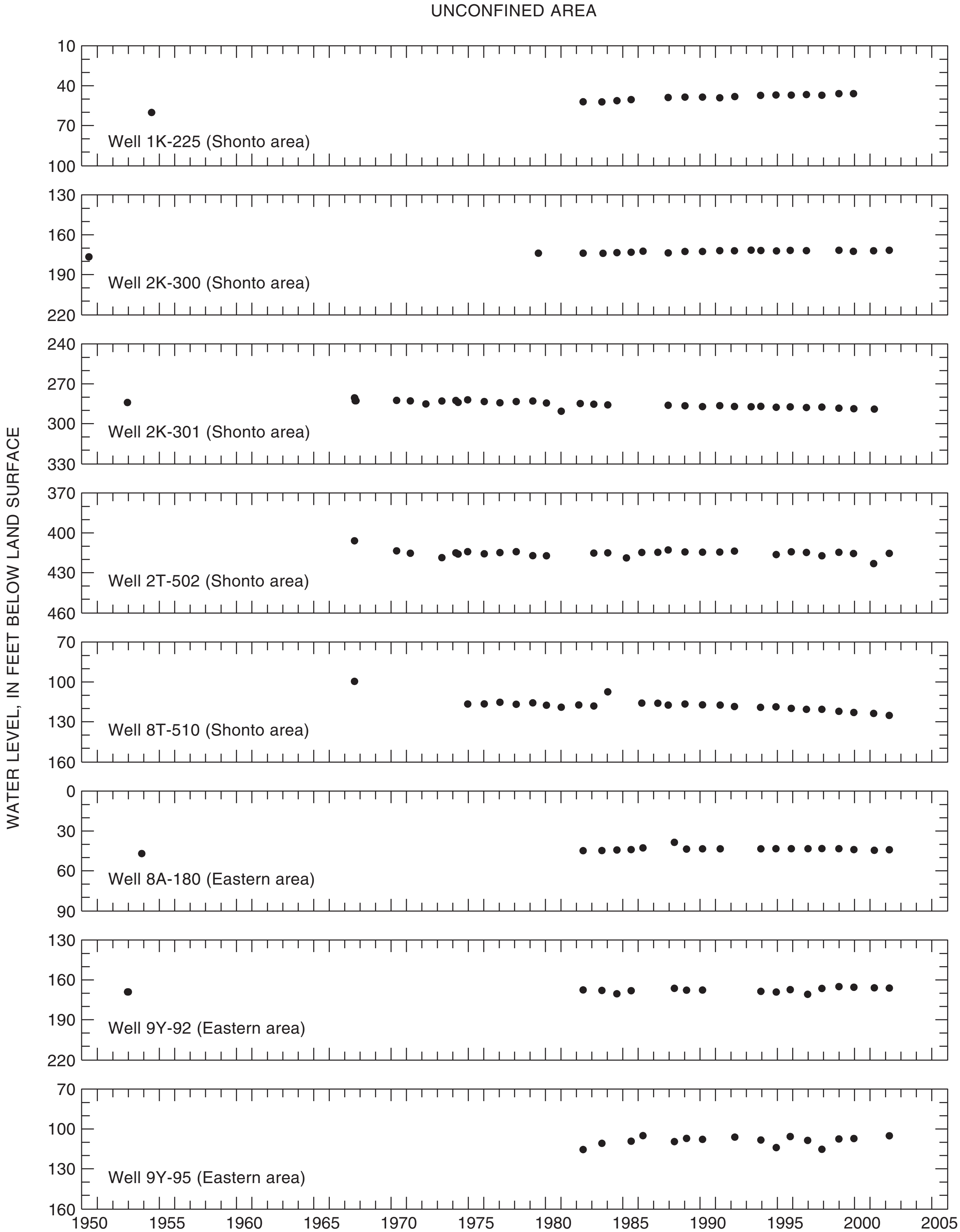


Figure 7. Observed water levels (1950–2002) in annual observation-well network, Black Mesa area, Arizona.



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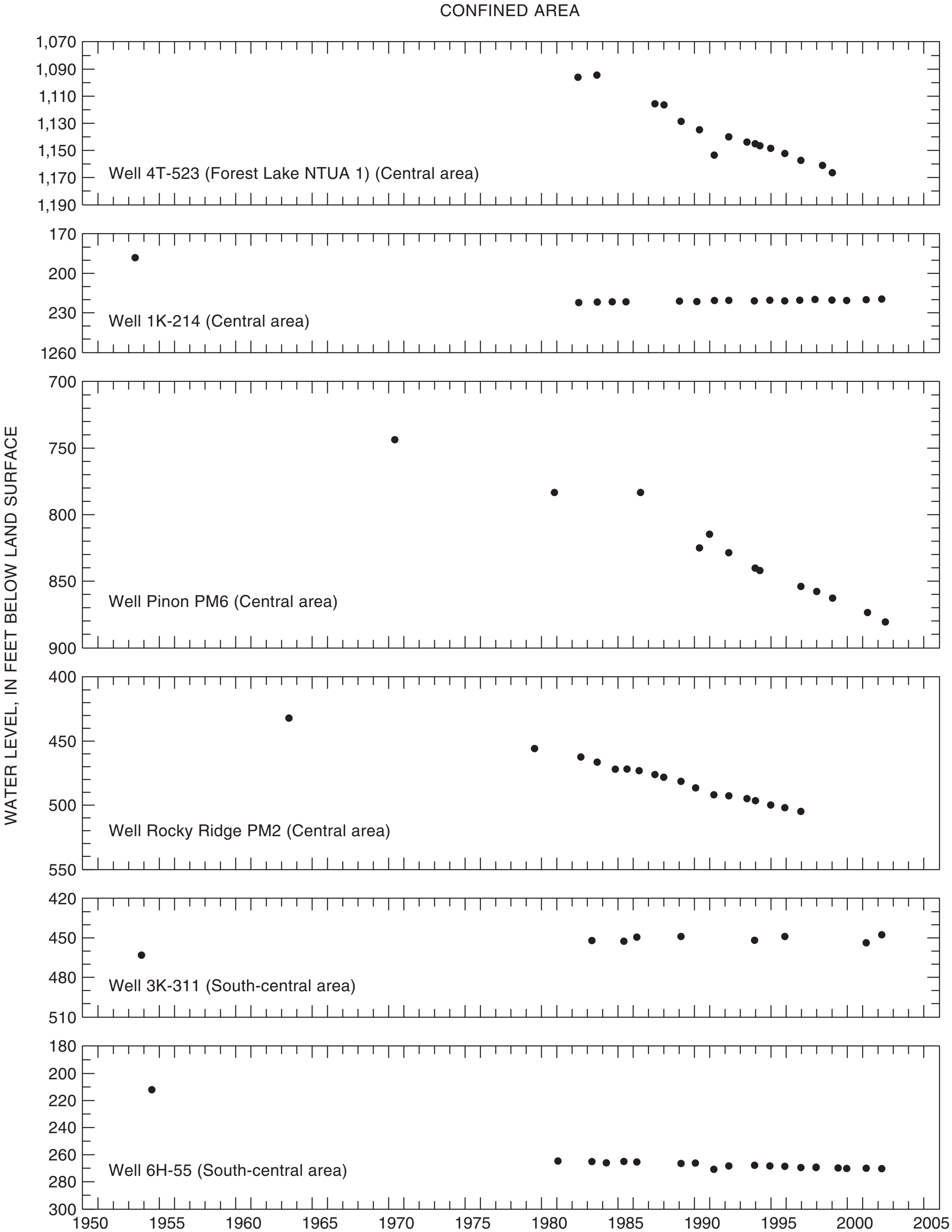

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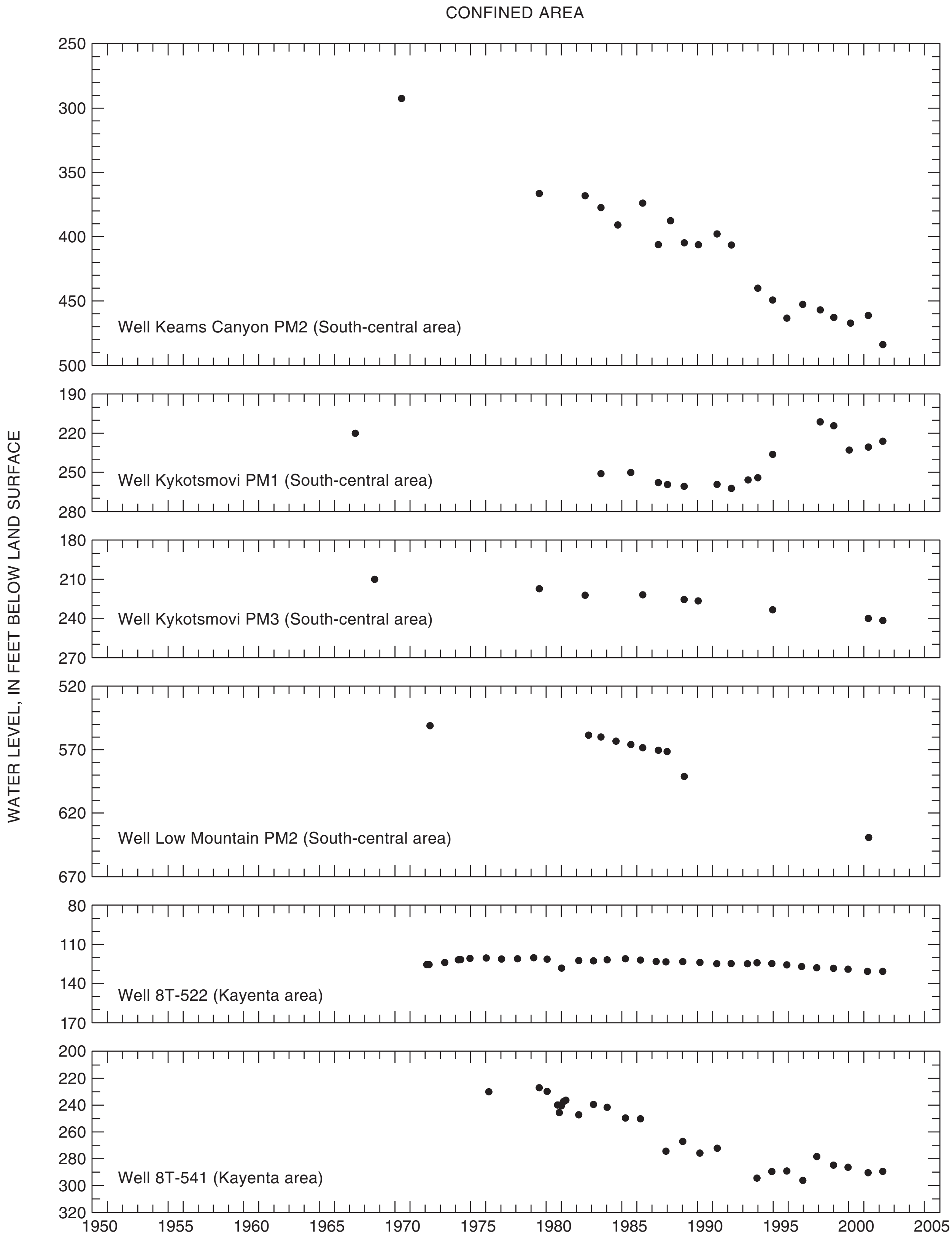

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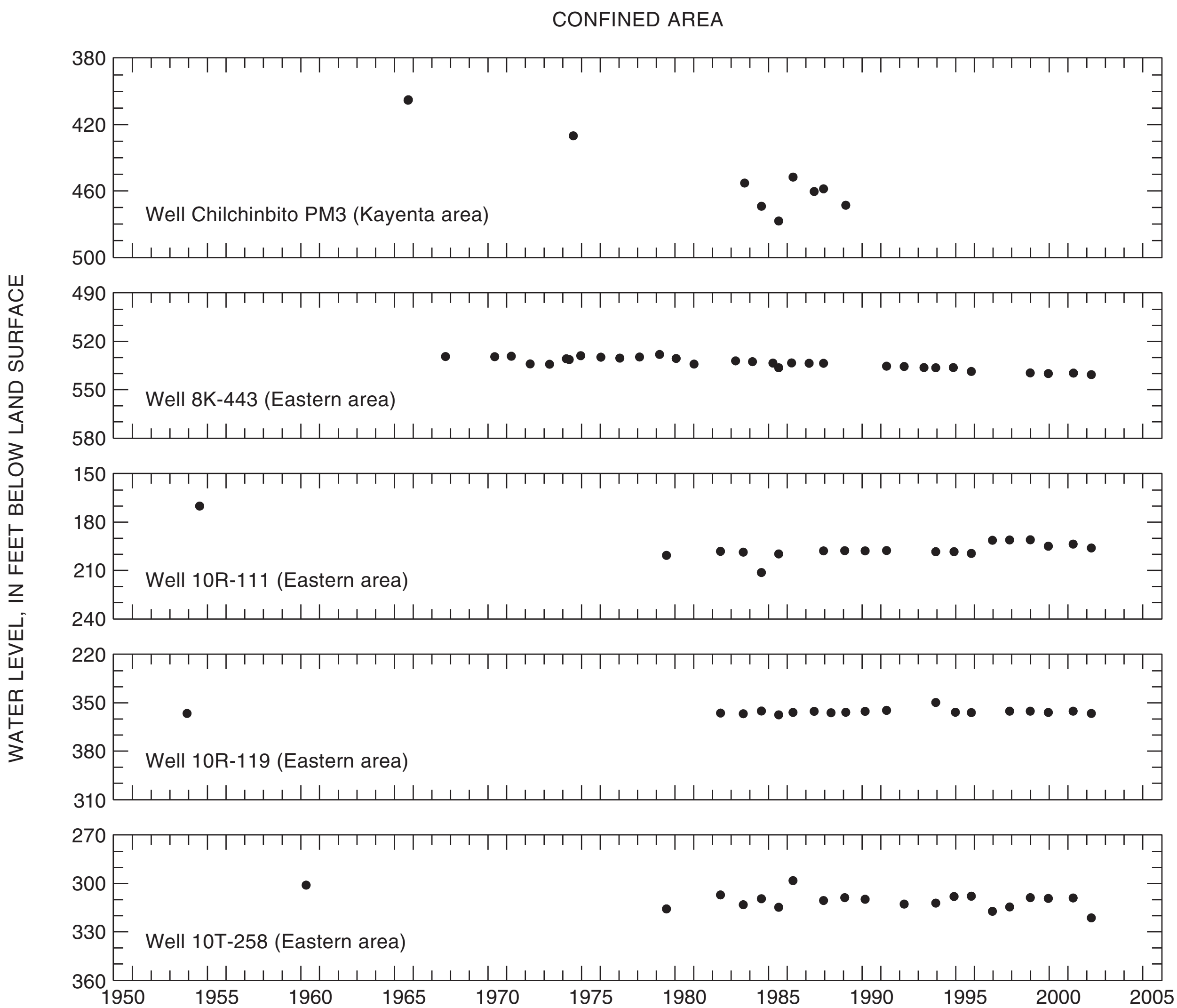

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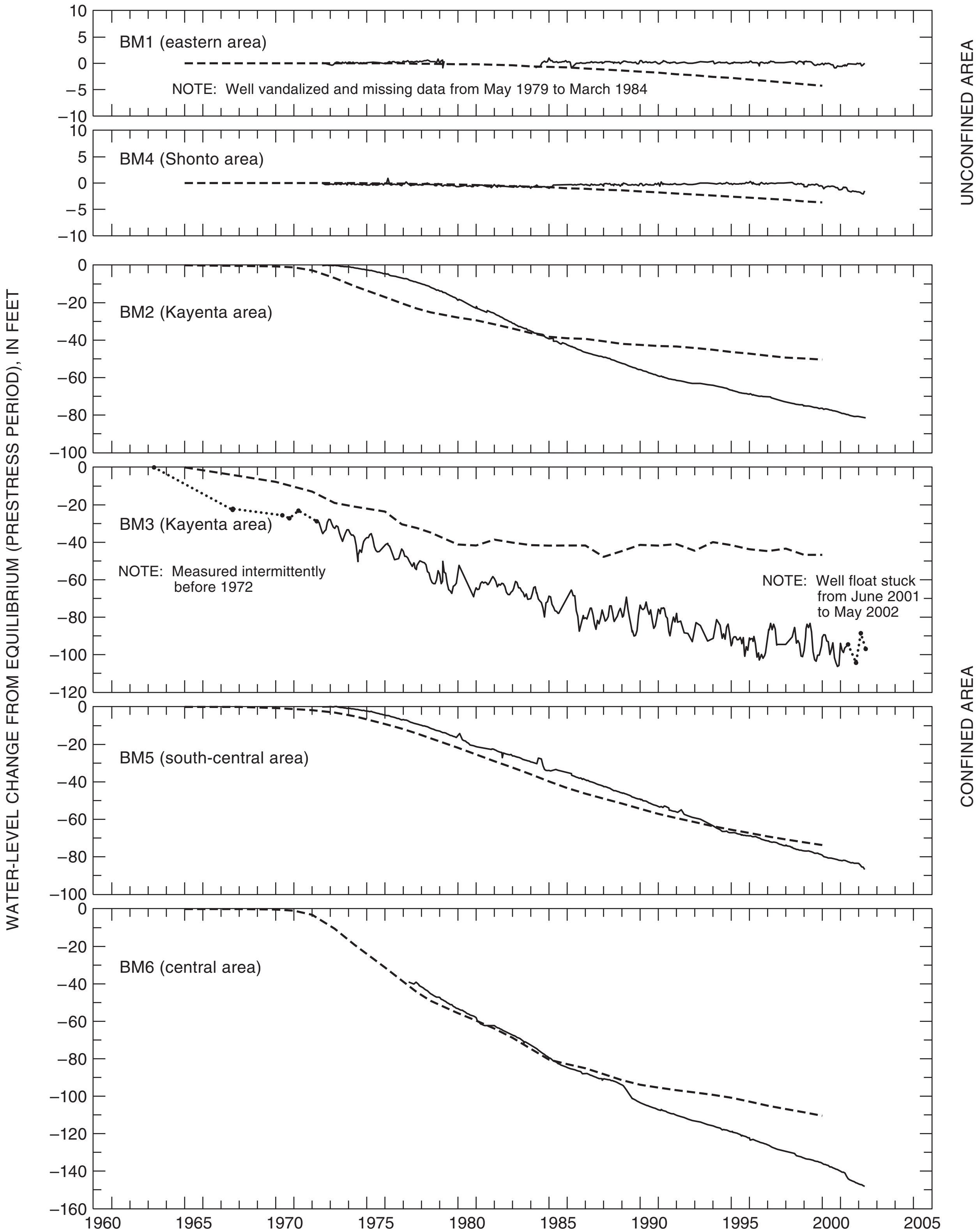

Figure 8. Observed water-level changes in continuous-record observation wells, BM1–BM6, 1963–2002 (solid line), and simulated water-level changes, 1965–99 (dashed line; Thomas, 2002), Black Mesa area, Arizona.

Table 6. Discharge measurements of selected springs, Black Mesa area, Arizona, 1952–2002

[All the measured discharges do not represent the total discharge from the springs]

Bureau of Indian Affairs site number	Rock formation(s)	Date of measurement	Discharge, in gallons per minute
Burro Spring			
6M-31	Navajo Sandstone	12–15–89	0.4
		12–13–90	0.4
		03–18–93	0.3
		12–08–94	0.2
		12–17–96	0.4
		12–30–97	0.2
		12–08–98	0.3
		12–07–99	0.3
		04–02–01	0.2
		04–04–02	0.4
Unnamed spring near Dennehotso			
8A-224	Navajo Sandstone	10–06–54	[3]1
		06–27–84	[3]2
		11–17–87	[3]5
		03–26–92	16
		10–22–93	14.4
		12–05–95	17
		12–19–96	15.7
		12–31–97	25.6
		12–14–98	21.0
		12–15–99	14.8
		03–14–01	26.8
		07–15–02	9.0

Bureau of Indian Affairs site number	Rock formation(s)	Date of measurement	Discharge, in gallons per minute
Moenkopi School Spring			
3GS-77-6	Navajo Sandstone[1]	05–16–52	40
		04–22–87	[2]16
		11–29–88	[2]12.5
		02–21–91	[2]13.5
		04–07–93	[2]14.6
		12–07–94	[2]12.9
		12–04–95	[2]12.1
		12–16-96	[2]10
		12–17–97	[2]13.1
		12–08–98	[2]12.0
		12–13–99	[2]13.3
		03–12–01	[2]13.7
		06–19–02	[2]10.2
Pasture Canyon Spring			
3A-5	Navajo Sandstone, alluvium	11–18–88	[4]211
		03–24–92	[4]233
		10–12–93	[4]211
		12–04–95	[5]38
		12–16–96	[5]38
		12–17–97	[5]40
		12–10–98	[5]39
		12–21–99	[5]39.0
		06–12–01	[5]37.0
		06–19–02	[5]37.0

[1]Tongue in the Kayenta Formation.
[2]Discharge measured at water-quality sampling site and at a different point than the measurement in 1952.
[3]Discharge measured at a different point than later measurements.
[4]Discharge measured in an irrigation ditch about 0.25 mile below water-quality sampling point.
[5]Discharge measured at water-quality sampling point about 20 feet below upper spring on west side of canyon.

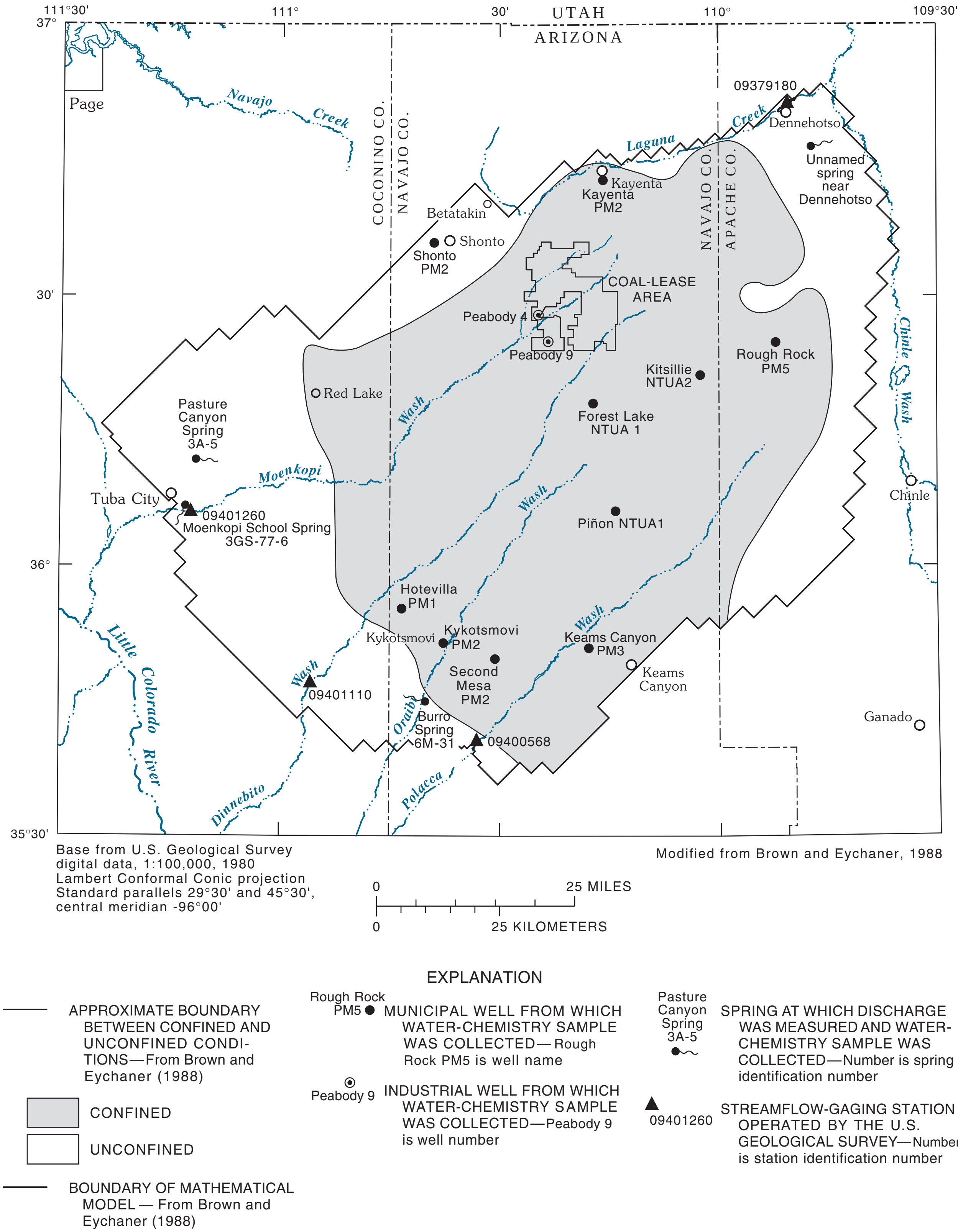

Figure 9. Surface-water and water-chemistry data-collection sites, Black Mesa area, Arizona, 2001–02.

In 2002, measured discharges were 0.4 gal/min from Burro Spring, 9.0 gal/min from the unnamed spring near Dennehotso, 10.2 gal/min from Moenkopi School Spring, and 37.0 gal/min from Pasture Canyon Spring. Compared with spring discharges in 2001, discharges increased by 100 percent for Burro Spring, decreased by 66 percent for the unnamed spring near Dennehotso, decreased by 26 percent for Moenkopi School Spring, and did not change for Pasture Canyon Spring.

Long-term changes in spring discharge can be evaluated for the entire record at Burro Spring but can be evaluated only for parts of the records for the other three springs because discharge measuring points changed during the periods of record. Consistent measuring points are available for 1992–2002 at the unnamed spring near Dennehotso, for 1987–2002 at Moenkopi School Spring, and for 1995–2002 at Pasture Canyon Spring (**table 6**). For the consistent periods of record at all four springs, the discharges have fluctuated; however, increasing or decreasing trends are not apparent (fig. 10).

Surface-Water Discharge

Surface-water discharge in the study area includes ground-water discharge and direct or shallow subsurface runoff of rainfall or snowmelt. Ground water discharges to surface water at a fairly constant rate throughout the year. In contrast, the amount of rainfall or snowmelt runoff varies widely throughout the year. In the winter and spring, the amount and timing of snowmelt runoff is a result of the temporal variation in snow accumulation, air temperatures, and rate of snowmelt. Although most rainfall runoff is in the summer, rainfall can cause surface-water discharge any time of the year. The amount and timing of rainfall runoff is a result of the intensity and duration of thunderstorms in the summer and cyclonic storms in the fall, winter, and spring.

Data on surface-water discharge have been collected continuously at selected streams each year of the monitoring program. The discharge data provide useful information about ground-water discharge and about runoff from rainfall and snowmelt. In this study, the total discharge in streams is roughly separated into ground-water discharge and runoff so that the temporal trends in ground-water discharge can be monitored.

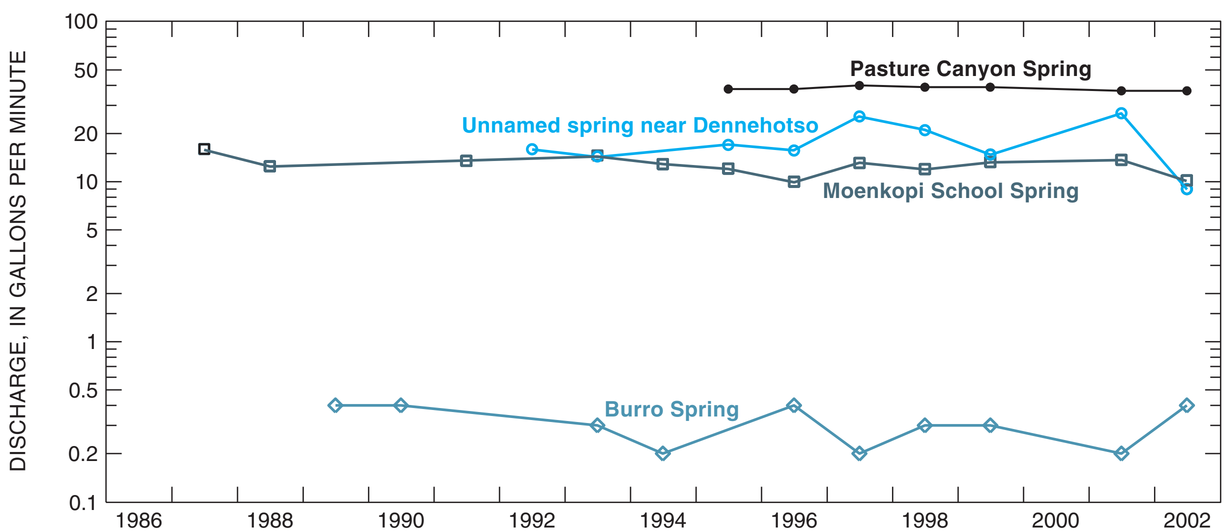

Figure 10. Discharge from selected springs, Black Mesa area, Arizona, 1987–2002.

In 2001, continuous-record discharge data were collected at four streamflow-gaging stations (tables 7–10). Data collection began at the gaging stations on July 1976 for Moenkopi Wash, July 1996 for Laguna Creek, June 1993 for Dinnebito Wash, and April 1994 for Polacca Wash (**fig. 9**, **table 11**).

The annual average discharges for the four gaging stations vary considerably during their periods of record (**fig. 11**). The discharges in Moenkopi Wash appear to have become more variable during the last 12 years with no long-term trend, discharges in Laguna Creek appear to have decreased the last 5 years, and discharges in Dinnebito Wash and Polacca Wash have been variable with no trend the last 7 years.

The ground-water discharge component of total flow at the four streamflow-gaging stations was estimated by computing the median flow for four winter months—November, December, January, and February. Ground-water discharge is assumed to be constant the entire year, and the median winter flow is assumed to represent this constant annual ground-water discharge. Most flow during the winter is ground-water discharge because rainfall and snowmelt runoff are minimal. Most of the precipitation in the winter falls as snow, and the cold temperatures prevent appreciable snowmelt. Also, evapotranspiration from streams is at a minimum during the winter. During the summer, much of the flow in streams evaporates or is transpired by plants. The median flow for November, December, January, and February, rather than the average flow, is used to estimate ground-water discharge because the median is less affected by occasional winter runoff. The 120 consecutive daily mean flows for those four months were used to compute the median flow.

The median flow for November, December, January, and February is an index of ground-water discharge rather than an absolute estimate of discharge. A more rigorous and accurate estimate would include detailed evaluations of streamflow hydrographs, flows into and out of bank storage, gain and loss of streamflow as it moves down the stream channel, and interaction of ground water in the N aquifer with ground water in the shallow alluvial aquifers in the stream valleys. The median winter flow, however, is useful as a consistent index for evaluating possible time trends in ground-water discharge.

Median winter flows were calculated for the 2001 water year, thus daily mean flows for November and December 2000 (Thomas, 2002) were combined with daily mean flows for January and February 2001. These median winter flows were 1.1 ft^3/s for Moenkopi Wash, 2.3 ft^3/s for Laguna Creek, 0.37 ft^3/s for Dinnebito Wash, and 0.11 ft^3/s for Polacca Wash. Since 1995, the median flows for Moenkopi Wash, Dinnebito Wash, and Polacca Wash have decreased (fig. 11). Median flows for Laguna Creek are only available since 1997, and there is no consistent trend in these flows. Annual precipitation at Betatakin, about 15 miles west of Kayenta, has been less than average for 5 of the 7 years since 1995 (fig. 11).

Water Chemistry

Water samples are collected from selected wells and springs each year of the Black Mesa monitoring program. Field measurements are made and water samples are analyzed for major ions, nutrients, iron, boron, and arsenic. During the past 10 years, water samples have been collected from about 30 different wells and 10 different springs. Samples are collected from about 12 wells and 4 springs in each year of the program. Samples are collected from about the same 8 wells every year and from the other 4 wells on a rotational basis. Since 1996, samples have been collected from the same 4 springs. Long-term data for specific conductance, total dissolved solids, chloride, and sulfate for the wells and springs sampled each year are shown in the report published for that year. Historical data for other constituents for all the wells and springs are available from the USGS water-quality database or can be found in the past monitoring reports that are cited in the “Previous Investigations” section of this report.

Water from Wells Completed in the N Aquifer

In 2002, water samples were collected from 12 wells completed in the N aquifer. Eleven of the wells are in confined parts of the aquifer, and one well (Shonto PM2) is in an unconfined part of the aquifer (fig. 9). The primary types of water in the N aquifer are calcium bicarbonate and sodium bicarbonate. Calcium bicarbonate water generally is in the recharge areas of the northern and northwestern parts of the Black Mesa area, and sodium bicarbonate water is in the area that is downgradient to the south and east (Thomas, 2002). In 2002, water samples from Kayenta PM2 and from Shonto PM2 in the north were calcium bicarbonate water, and samples from the other 10 wells were sodium bicarbonate water (**fig. 12**). Dissolved-solids concentrations in water from the 12 wells ranged from 96 mg/L at Peabody 9 to 636 mg/L at Rough Rock PM5 (**table 12**, fig. 12).

Table 7. Discharge data, Moenkopi Wash at Moenkopi, Arizona (09401260), calendar year 2001

[dashes indicate no data. AC-FT, acre-feet]

Discharge, in cubic feet per second, calendar year 2001 Daily mean values												
Day	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.[1]**	**Nov.[1]**	**Dec.[1]**
1	[2]0.73	[2]1.6	2.5	1.1	1.5	0.0	0.0	0.0	0.06	0.0	1.1	2.4
2	[2].73	[2]1.6	1.9	0.94	1.4	.0	.0	.0	.0	.0	1.1	2.2
3	[2].65	2.5	2.6	1.3	1.6	.0	.0	.0	.0	.0	1.1	2.1
4	[2].60	2.4	2.2	2.1	1.8	.0	.0	.0	.0	.0	1.1	2.4
5	[2].55	2.0	1.7	2.3	1.9	.0	.0	1,140	.0	.0	1.1	2.8
6	[2].64	2.4	1.8	5.6	1.6	.0	.0	83	.0	.01	1.1	1.7
7	[2].75	2.2	3.1	7.7	1.5	.0	14	15	.0	7.2	1.1	1.3
8	[2].81	2.1	3.4	3.5	1.3	.0	16	[2]13	.0	2.3	1.4	1.8
9	[2].75	2.0	2.3	2.3	1.1	.0	127	[2]73	.0	.94	1.5	2.1
10	[2]2.2	1.6	4.2	2.1	.89	.0	129	[2]12	.0	.58	1.3	2.1
11	[2]2.1	1.9	6.6	4.3	.49	.0	891	1,510	.0	.58	1.1	3.4
12	[2]1.8	1.6	7.3	3.6	.32	.0	[2]28	956	.0	.56	1.1	3.3
13	[2]1.5	1.6	4.7	2.9	.34	.0	7.0	259	.0	.58	1.1	2.4
14	[2]1.1	1.9	3.7	3.1	.70	.0	.82	261	.0	.58	1.5	2.0
15	[2]1.0	1.4	3.8	3.7	.50	.0	.06	187	1.9	.75	1.5	2.7
16	[2].95	2.0	3.5	3.8	.22	.0	[2].40	90	4.9	.63	1.5	2.0
17	[2].84	2.0	3.6	4.7	.09	.0	[2].10	438	79	.58	1.2	2.1
18	[2].89	2.3	3.4	4.6	.05	.0	[2].20	178	51	.58	1.4	2.3
19	[2]1.0	2.0	3.4	4.1	.11	.0	[2].0	75	3.3	.58	1.4	2.0
20	[2]1.1	1.8	3.3	4.2	28	.0	[2].0	30	.06	.58	1.5	2.5
21	[2]1.2	1.9	2.8	4.7	4.5	.0	[2].0	22	.02	.73	1.5	2.9
22	[2]1.3	1.6	3.6	4.7	[2].22	.0	.0	134	.01	.95	1.5	2.6
23	[2]1.4	1.2	2.8	1.7	[2].40	.0	.0	[2]35	.0	.83	1.5	2.7
24	[2]1.5	1.1	2.5	2.1	[2].40	.0	.0	[2].83	.0	.81	1.2	3.3
25	1.5	.96	2.1	2.2	.17	.0	.0	.01	.0	.83	1.9	2.9
26	1.2	2.0	2.0	2.4	.03	.0	.0	.0	.0	.83	3.2	16
27	2.1	2.4	2.1	2.6	.0	.0	.0	.0	.0	.84	1.7	13
28	2.0	3.1	2.3	2.6	.0	.0	.0	.0	.0	1.1	2.4	3.6
29	1.6	---	1.5	2.2	.0	.0	.0	.0	.0	.83	3.5	3.6
30	[2]1.4	---	1.6	1.9	.0	.0	.0	70	.0	.83	3.7	3.3
31	[2]1.4	---	1.3	---	.0	---	.0	9.9	---	.86	---	2.5
TOTAL	37.29	53.16	93.6	95.04	51.13	0.0	1,213.58	5,591.74	140.25	26.47	47.3	102.0
MEAN	1.20	1.90	3.02	3.17	1.65	.0	39.1	180	4.68	0.85	1.6	3.3
MAX	2.2	3.1	7.3	7.7	28	.0	891	1,510	79	7.2	3.7	16
MIN	0.55	0.96	1.3	0.94	0.0	.0	0.0	0.0	0.0	0.0	1.1	1.3
AC-FT	74	105	186	189	101	.0	2,410	11,090	278	53	94	202
CALENDAR YEAR 2001			TOTAL 7,451.56		MEAN 20.42		MAXIMUM 1,510		MINIMUM 0.0		AC-FT 14,780	

[1]Month in which data are provisional, subject to revision.
[2]Estimated.

Table 8. Discharge data, Laguna Creek at Dennehotso, Arizona (09379180), calendar year 2001

[Dashes indicate no data. AC-FT, acre-feet]

Discharge, in cubic feet per second, calendar year 2001 Daily mean values												
Day	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.[1]**	**Nov.[1]**	**Dec.[1]**
1	[2]4.7	[2]2.3	7.2	0.60	[2]0.13	0.0	0.0	0.0	0.0	0.0	0.64	1.8
2	3.9	[2]2.1	5.6	.57	[2].0	.0	.0	.0	.0	.0	.63	[2]3.5
3	[2]5.2	[2]2.0	4.4	.41	.0	.0	.0	.0	.0	.0	.96	[2]5.1
4	[2]2.5	[2]5.0	4.1	.07	.0	.0	.0	.0	.0	.0	1.2	[2]4.9
5	[2]2.0	[2]7.5	2.5	.0	.0	.0	.0	[2].0	.0	.0	1.4	[2]4.3
6	[2]1.2	[2]7.0	1.5	.0	.0	.0	.0	[2]9.7	.0	.0	1.4	[2]2.5
7	[2]1.4	[2]10	1.2	5.3	[2].02	.0	.0	2.6	.0	.0	2.0	[2]1.3
8	[2]1.4	13	46	20	[2].0	.0	.0	9.7	.0	.0	2.9	[2].60
9	[2]1.0	8.3	25	8.4	.0	.0	.0	46	.0	.0	2.9	[2].37
10	[2]1.6	[2]3.8	8.9	6.7	.21	.0	454	57	.0	.0	2.6	[2].58
11	[2]2.5	[2]3.2	2.6	2.1	.0	.0	138	[2]8.5	.0	.0	2.7	[2].92
12	[2]3.0	1.6	3.4	1.6	.0	.0	14	11	.0	.0	2.5	[2]1.4
13	[2]5.0	2.6	[2]3.1	4.0	.0	.0	5.3	4.6	.0	.0	3.1	[2]1.1
14	[2]1.5	1.9	4.8	3.7	26	.0	1.3	6.0	.0	.0	3.3	.41
15	[2]0.50	0.66	2.6	3.1	4.2	.0	35	2.4	.0	.0	1.5	.08
16	[2]1.1	.89	1.5	1.6	.05	.0	9.3	.43	.0	.0	4.1	[2].20
17	[2]1.4	[2]2.8	[2]0.70	.66	.0	.0	2.1	189	.0	.0	3.6	.01
18	[2]1.9	[2]5.0	.87	.49	.0	.0	.16	19	.0	.0	3.0	.05
19	[2].70	2.3	.69	.07	.0	.0	.01	4.7	.0	.0	2.9	[2].35
20	[2].50	[2]1.5	.56	.0	110	.0	.0	.46	.0	.0	2.6	[2].39
21	1.7	2.3	.36	.0	10	.0	.0	4.0	.0	.83	2.6	[2].49
22	[2]1.5	1.1	.36	.0	1.7	.0	.0	19	.0	.10	2.6	[2].72
23	[2]4.5	1.5	.53	.0	.54	.0	.0	1.8	.0	.0	.36	[2].97
24	[2]5.0	1.5	2.4	.0	.04	.0	.0	1.2	.0	.06	[2]1.9	[2].42
25	[2]6.5	1.2	2.2	[2].10	.0	.0	.0	1.1	.0	.04	[2]1.9	[2].29
26	[2]5.0	1.1	1.7	[2].40	.0	.0	.0	.19	.0	.11	[2]1.4	[2].23
27	[2]9.0	2.1	1.4	[2]8.3	.0	.0	.0	.0	.0	.14	[2]1.5	[2].59
28	9.0	[2]5.5	1.2	.0	.0	.0	.0	.0	.0	.19	[2]1.8	[2]2.4
29	[2]5.5	---	1.0	.0	.0	.0	.0	.0	.0	.37	[2]2.1	[2]4.0
30	[2]5.0	---	.80	[2].17	.0	.0	.0	.0	.0	.40	[2]1.6	[2]4.2
31	[2]5.0	---	.69	---	.0	---	.0	.0	---	.67	---	[2]3.2
TOTAL	100.70	99.75	139.86	68.34	152.89	0.0	659.17	398.38	0.0	2.91	63.69	47.37
MEAN	3.25	3.56	4.51	2.28	4.93	.0	21.3	12.9	.0	.09	2.12	1.53
MAX	9.0	13	46	20	110	.0	454	189	.0	.83	4.1	5.1
MIN	0.50	0.66	0.36	0.0	0.0	.0	0.0	0.0	.0	.0	.36	.01
AC-FT	200	198	277	136	303	.0	1,310	790	.0	5.8	126	94
CALENDAR YEAR 2001			TOTAL 1,733.06		MEAN 4.75		MAXIMUM 454		MINIMUM 0.0		AC-FT 3,440	

[1]Month in which data are provisional, subject to revision.
[2]Estimated.

Table 9. Discharge data, Dinnebito Wash near Sand Springs, Arizona (09401110), calendar year 2001

[Dashes indicate no data. AC-FT, acre-feet]

Discharge, in cubic feet per second, calendar year 2001 Daily mean values												
Day	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**[1]	**Nov.**[1]	**Dec.**[1]
1	0.34	0.37	0.48	0.36	0.36	0.20	0.18	0.19	0.22	0.13	0.43	0.26
2	.35	.42	.43	.34	.32	.18	.18	1.1	.20	.14	.40	.28
3	.35	.45	.55	.32	.33	.17	.17	22	.20	.16	.41	.27
4	.34	.47	.47	.34	.35	.17	.16	55	.20	.17	.42	.40
5	.34	.48	.43	.35	.39	.18	.16	140	.19	.18	.39	.35
6	.41	.49	.43	.89	.36	.18	.17	13	.16	.19	.38	.24
7	.39	.47	.56	.44	.35	.19	.20	5.4	.16	.32	.40	.24
8	.41	.44	.60	.36	.36	.18	.20	2.2	.17	.25	.40	.23
9	.59	.41	.44	.36	.35	.16	.21	21	.18	.22	.40	.22
10	.52	.43	.59	.40	.32	.16	[2]193	7.6	.08	.22	.39	.24
11	.46	.42	.79	.44	.31	.15	[2]30	556	.07	.24	.38	.25
12	.47	.41	.52	.38	.30	.14	[2]15	204	.15	.23	.36	.24
13	.42	.40	.38	.40	.32	.13	2.4	30	.17	.24	.36	.18
14	.39	.50	.45	.41	.33	.16	.89	16	.18	.28	.35	.09
15	.41	.44	.37	.41	.31	.18	6.8	5.8	.19	.30	.34	.08
16	.47	.42	.40	.42	.30	.17	39	24	.18	.30	.34	.41
17	.47	.44	.39	.41	.30	.16	7.6	4.0	7.4	.33	.33	.21
18	.32	.46	.39	.39	.31	.15	1.5	13	9.9	.34	.32	.21
19	.31	.44	.41	.33	.40	.14	.32	4.0	7.3	.34	.32	.21
20	.37	.43	.42	.32	.48	.14	.25	.65	1.1	.35	.31	.23
21	.38	.43	.42	.31	.30	.14	.20	6.7	.28	.38	.30	.26
22	.44	.44	.41	.36	.28	.14	.17	.42	.24	.40	.31	.22
23	.52	.40	.42	.36	.27	.13	.15	.31	.23	.41	.70	.19
24	.54	.38	.43	.38	.27	.16	.15	.24	.22	.39	.33	7.6
25	.49	.39	.43	.39	.25	.16	.17	.23	.22	.43	.34	.18
26	.45	.52	.43	.38	.23	.18	.24	.21	.22	.46	.29	.14
27	.52	.51	.40	.38	.22	.17	.16	.21	.22	.47	.25	.20
28	.50	.65	.39	.42	.22	.16	.14	.20	.15	.43	.21	.28
29	.44	---	.37	.37	.21	.15	.14	5.4	.12	.43	.25	.40
30	.44	---	.38	.36	.21	.16	.14	1.3	.14	.44	.28	.57
31	.37	---	.36	---	.20	---	.26	.25	---	.44	---	.47
TOTAL	13.22	12.51	13.94	11.78	9.51	4.84	300.31	1,140.41	30.44	9.61	10.69	15.35
MEAN	0.43	0.45	0.45	0.39	0.31	0.16	9.69	36.8	1.01	0.31	0.36	0.50
MAX	.59	.65	.79	.89	.48	.20	193	556	9.9	.47	.70	7.6
MIN	.31	.37	.36	.31	.20	.13	0.14	0.19	0.07	.13	.21	.08
AC-FT	26	25	28	23	19	9.6	596	2,260	60	19	21	30
CALENDAR YEAR: 2001			TOTAL 1,572.61		MEAN 4.31		MAXIMUM 556		MINIMUM 0.0		AC-FT 3,119	

[1]Month in which data are provisional, subject to revision.
[2]Estimated.

Table 10. Discharge data, Polacca Wash near Second Mesa, Arizona (09400568), calendar year 2001

[Dashes indicate data. AC-FT, acre-feet]

Discharge, in cubic feet per second, calendar year 2001 Daily mean values												
Day	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.[1]**	**Nov.[1]**	**Dec.[1]**
1	0.06	[2]0.16	0.16	0.17	0.13	0.07	0.01	0.15	0.10	0.0	0.05	0.07
2	.07	[2].17	.15	.16	.11	.07	.01	.01	.09	.0	.05	.08
3	.06	.18	.14	.15	.15	.05	.01	.0	.08	.0	.05	.09
4	.07	.18	.13	.15	.15	.05	.01	.0	.06	.0	.05	.09
5	.07	.18	.13	.15	.16	.07	.01	.0	.03	.0	.05	.12
6	.10	.19	.12	.72	.13	.08	.0	16	.01	.0	.06	.09
7	.08	.16	.15	.20	.12	.08	.01	27	.0	.01	.05	.08
8	.10	.17	.14	.16	.12	.08	.02	3.5	.0	.01	.06	.06
9	.47	.16	.13	.15	.12	.07	.02	.04	.0	.01	.06	.05
10	.19	.16	1.9	.18	.11	.06	201	102	.0	.01	.06	.09
11	.16	.14	3.4	.18	.10	.06	73	95	.0	.01	.06	.07
12	[2].15	.14	2.0	.18	.10	.05	54	115	.0	.01	.06	.07
13	[2].16	.15	1.2	.17	.33	.04	3.3	96	.0	.01	.06	.03
14	[2].15	.26	.32	.16	.47	.07	2.5	57	.0	.02	.05	.04
15	[2].13	.17	.20	.16	.12	.08	71	11	.01	.02	.06	.09
16	[2].12	.15	.18	.16	.10	.08	45	41	.0	.02	.06	.07
17	[2].11	.15	.18	.15	.11	.08	2.3	.50	.0	.02	.06	.05
18	.11	.16	.19	.14	.10	.07	.24	.14	76	.03	.06	.06
19	.09	.14	.19	.13	.19	.05	.10	.08	5.2	.03	.06	.06
20	[2].13	.13	.18	.13	.20	.05	.05	.06	.04	.03	.06	.09
21	[2].13	.13	.18	.13	.11	.05	.03	.71	.02	.04	.06	.10
22	[2].14	.14	.19	.16	.09	.05	.03	152	.01	.05	.06	.08
23	[2].18	.14	.19	.15	.09	.05	.02	92	.01	.04	.10	.06
24	.24	.12	.16	.15	.08	.06	.02	5.2	.01	.04	.06	.13
25	.20	.12	.19	.15	.07	.08	.02	1.1	.01	.04	.10	.08
26	.18	.29	.18	.14	.07	.08	.04	.64	.01	.05	.06	.08
27	[2].18	.16	.17	.17	.07	.06	.02	.49	.01	.05	.06	.13
28	[2].18	.27	.17	.17	.08	.02	.02	.39	.0	.05	.04	.16
29	[2].17	---	.17	.14	.07	.01	.01	.33	.0	.05	.08	.18
30	.17	---	.16	.13	.08	.01	.0	.29	.0	.05	.08	.18
31	.16	---	.16	---	.07	---	.0	.19	---	.05	---	.44
TOTAL	4.51	4.67	13.11	5.24	4.00	1.78	452.80	817.82	81.70	0.75	1.83	3.07
MEAN	0.15	0.17	0.42	0.17	0.13	0.06	14.6	26.4	2.72	.02	0.06	0.10
MAX	.47	.29	3.4	.72	.47	.08	201	152	76	.05	.10	.44
MIN	.06	.12	.12	.13	.07	.01	0.0	0.0	0.0	.0	.04	.03
AC-FT	8.9	9.3	26	10	7.9	3.5	898	1,620	162	1.5	3.6	6.1
CALENDAR YEAR 2001			TOTAL 1,391.28		MEAN 3.81		MAXIMUM 201		MINIMUM 0.0		AC-FT 2,760	

[1]Month in which data are provisional, subject to revision.
[2]Estimated.

Table 11. Date that data collection began and drainage areas for streamflow-gaging stations, Black Mesa area, Arizona

Station name	Station number	Date data collection began	Drainage area, in square miles
Moenkopi Wash at Moenkopi	09401260	July 1976	1,629
Laguna Creek at Dennehotso	09379180	July 1996	414
Dinnebito Wash near Sand Springs	09401110	June 1993	473
Polacca Wash near Second Mesa	09400568	April 1994	905

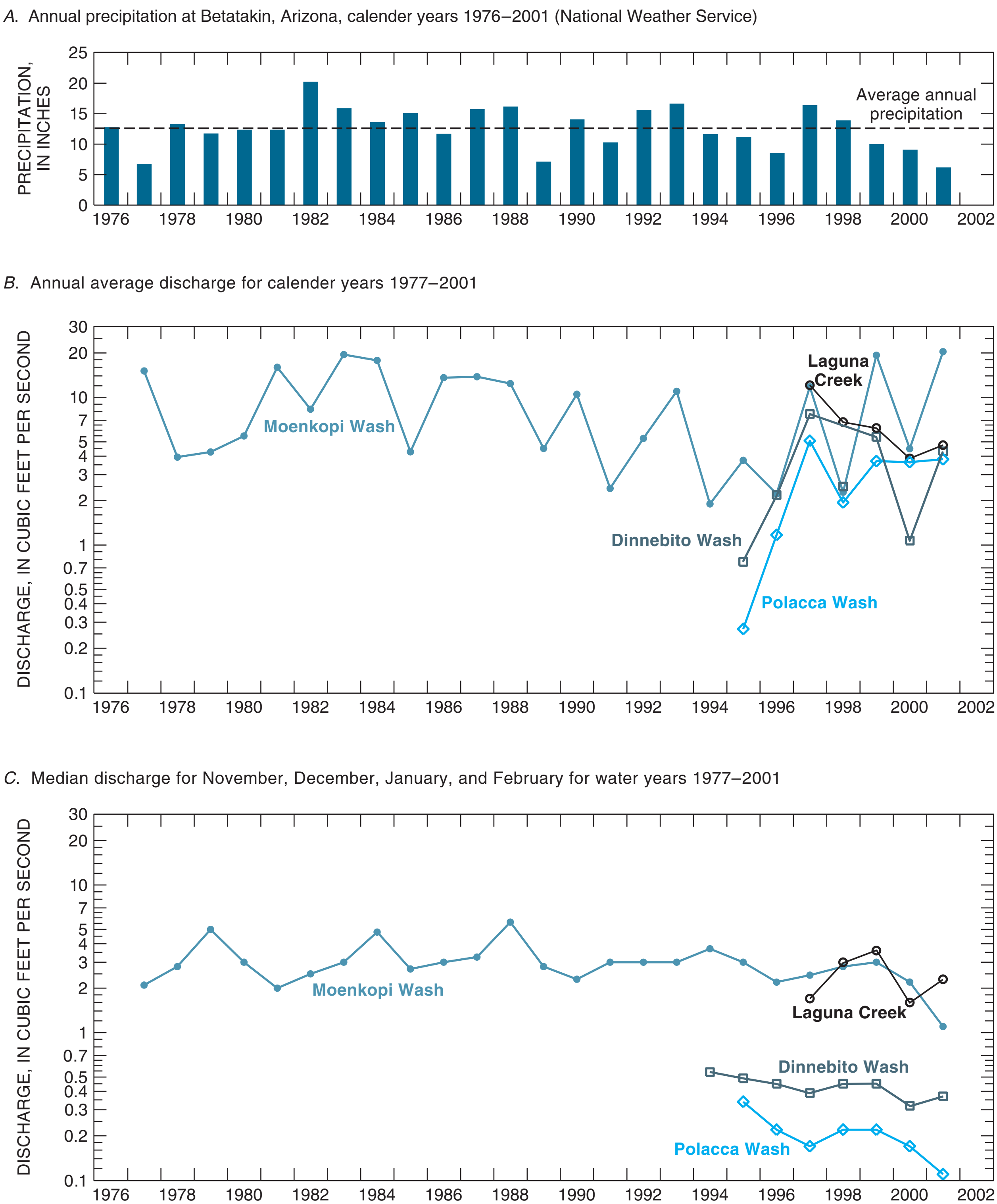

Figure 11. Annual precipitation at Betatakin, Arizona, and streamflow characteristics at Moenkopi Wash (09401260), Laguna Creek (09379180), Dinnebito Wash (09401110), and Polacca Wash (09400568), Black Mesa area, Arizona. *A*, Annual precipitation at Betatakin, Arizona, calendar years 1976–2001 (National Weather Service). *B*, Annual average discharge for calendar years 1977–2001. *C*, Median discharge for November, December, January, and February for water years 1977–2001.

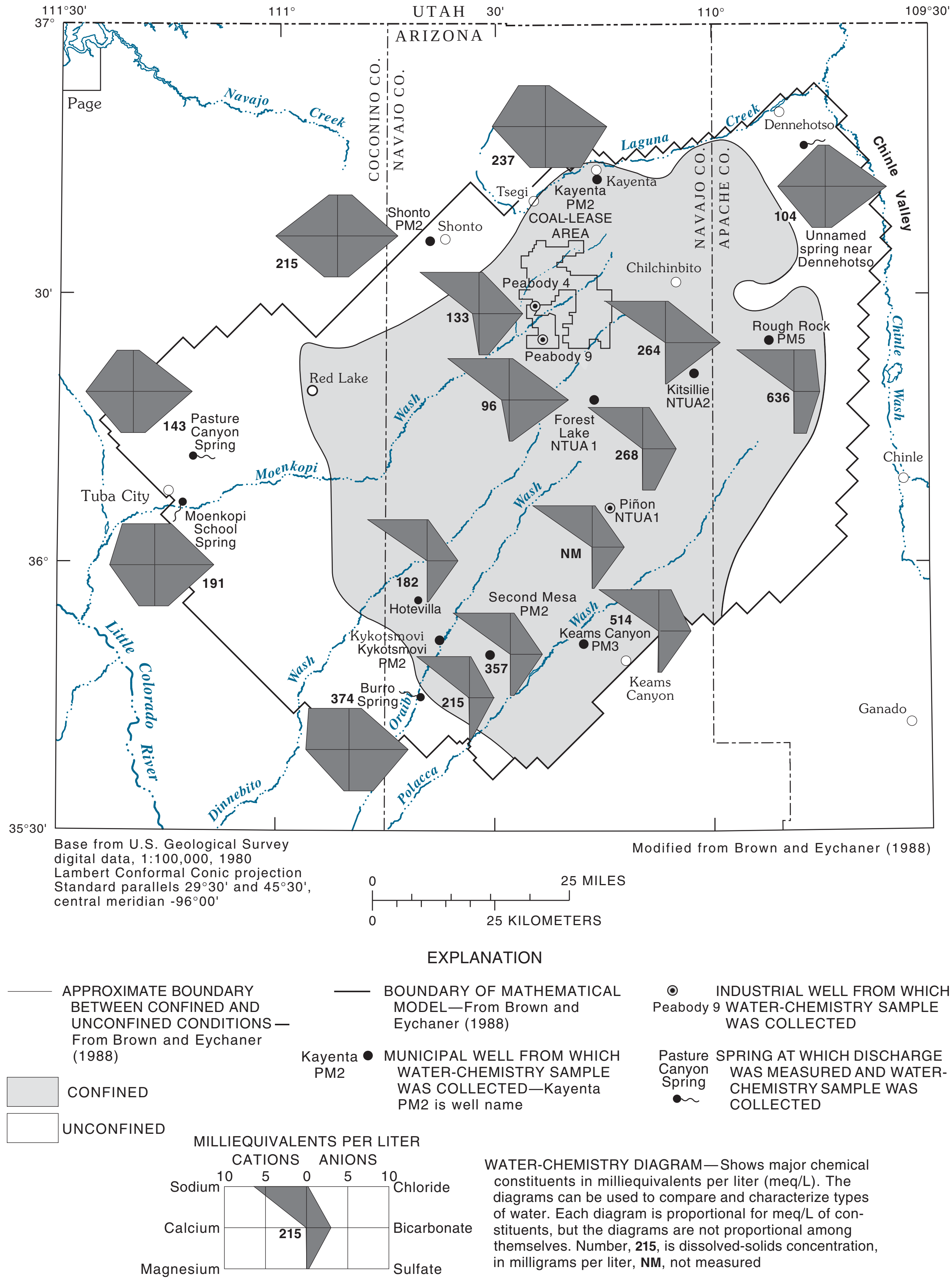

Figure 12. Water chemistry and distribution of dissolved solids in the N aquifer, Black Mesa area, Arizona, 2002.

Table 12. Physical properties and chemical analyses of water from selected industrial and municipal wells completed in the N aquifer, Black Mesa area, Arizona, 2002

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than. Dashes indicate no data]

Common well name	U.S. Geological Survey identification number	Date of sample	Temperature, field (°C)	Specific conductance, field (µS/cm)	pH, field (units)
Forest Lake NTUA1	361737110180301	04-04-02	23.3	452	9.0
Hotevilla PM1	355518110400301	04-02-02	26.2	287	9.4
Kayenta PM2	364344110151201	04-02-02	15.4	363	7.9
Keams Canyon PM3	355034110183001	04-01-02	21.0	870	9.3
Kitsillie NTUA 2	362043110030501	04-04-02	13.9	439	9.3
Kykotsmovi PM2	355215110375001	04-03-02	22.6	350	9.7
Peabody 4	362647110243501	04-03-02	32.3	214	8.8
Peabody 9	362333110250001	04-05-02	32.3	152	9.2
Piñon NTUA1	360527110122501	05-02-02	27.0	512	9.8
Rough Rock PM5	362418109514601	04-02-02	21.7	1,120	8.6
Second Mesa PM2	354749110300101	04-03-02	20.5	608	9.6
Shonto PM2	363558110392501	04-01-02	14.0	355	7.4

Common well name	Alkalinity, field, dissolved (mg/L as $CaCO_3$)	Nitrogen NO_2+NO_3 dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)
Forest Lake NTUA1	150	0.53	<0.02	0.71	0.08
Hotevilla PM1	142	1.0	.02	.64	.02
Kayenta PM2	120	.90	<.20	42	7.3
Keams Canyon PM3	310	<.05	<.20	.65	.12
Kitsillie NTUA 2	227	1.4	<.20	.49	.01
Kykotsmovi PM2	166	1.2	.02	.44	.01
Peabody 4	72	.97	<.02	4.1	.03
Peabody 9	80	.74	<.02	3.5	.03
Piñon NTUA1	236	1.3	<.02	.45	.01
Rough Rock PM5	239	1.0	<.02	2.0	.27
Second Mesa PM2	280	<.05	<.02	.42	.03
Shonto PM2	127	4.3	.09	52	6.6

See footnote at end of table.

Table 12. Physical properties and chemical analyses of water from selected industrial and municipal wells completed in the N aquifer, Black Mesa area, Arizona, 2002—Continued

Common well name	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)
Forest Lake NTUA1	99	0.60	22	50	0.5
Hotevilla PM1	66	.43	1.3	4.8	.2
Kayenta PM2	25	1.3	5.1	67	.2
Keams Canyon PM3	200	.62	63	26	1.0
Kitsillie NTUA 2	97	.55	4.5	4.4	1.1
Kykotsmovi PM2	78	.37	3.4	7.9	.2
Peabody 4	41	.67	3.9	13	.2
Peabody 9	31	.55	1.7	2.5	.2
Piñon NTUA1	110	.38	5.0	5.5	.2
Rough Rock PM5	230	1.3	130	110	1.8
Second Mesa PM2	130	.42	7.5	14	.3
Shonto PM2	8.0	1.8	22	22	[1].1

Common well name	Silica, dissolved (mg/L as SiO_2)	Arsenic, dissolved (μg/L as As)	Boron, dissolved (μg/L as B)	Iron, dissolved (μg/L as Fe)	Dissolved solids, residue at 180°C, (mg/L)
Forest Lake NTUA1	19	2.9	170	20	268
Hotevilla PM1	22	3.4	21	<10	182
Kayenta PM2	16	1.8	26	<10	237
Keams Canyon PM3	12	35	470	<10	514
Kitsillie NTUA 2	25	4.1	44	<10	264
Kykotsmovi PM2	23	5.4	29	<10	215
Peabody 4	21	2.9	22	<10	133
Peabody 9	19	3.1	20	<10	96
Piñon NTUA1	26	4.6	60	<10	---
Rough Rock PM5	12	51	420	<10	636
Second Mesa PM2	20	18	92	<10	357
Shonto PM2	14	0.8	[1]9	<10	215

[1]Estimated value.

Two wells had appreciably higher concentrations of dissolved solids and chloride than the other 10 wells; Keams Canyon PM3 had a dissolved-solids concentration of 514 mg/L and a chloride concentration of 63 mg/L, and Rough Rock PM5 had a dissolved-solids concentration of 636 mg/L and a chloride concentration of 130 mg/L. Concentrations of dissolved solids in water samples from the other 10 wells ranged from 96 to 357 mg/L, and concentrations of chloride ranged from 1.3 to 22 mg/L. The areal distribution of dissolved solids generally was similar to the distribution of water types. Lower concentrations of dissolved solids are in or near the recharge areas of the north and northwest, and higher concentrations of dissolved solids are in areas to the south and east (**fig. 12**).

There are no appreciable time trends in the chemistry of water samples from 9 wells having more than 7 years of data (**table 13**, **fig. 13**). The time periods of the water-chemistry data from these wells range from 1961–2002 to 1990–2002. In 7 of the 9 wells, there were small year-to-year variations in concentrations of dissolved solids, chloride, and sulfate; however, increasing or decreasing trends are not apparent. For the Shonto PM2 well, there may be an increasing trend in dissolved-solids and chloride concentrations; however, another few years of data are needed to confirm this possible trend. For the Forest Lake NTUA 1 well, the chemistry of water samples has varied considerably between 1982 and 2002. This variation may be from insufficient purging of this deep well (2,674 ft) that has multiple screens throughout an interval of about 800 ft from the lowest to highest screen (**table 5**).

Analyzed constituents from the 12 well samples were compared to U.S. Environmental Protection Agency (USEPA) Primary and Secondary Drinking-Water Regulations (U.S. Environmental Protection Agency, 2002). Maximum Contaminant Levels (MCLs), which are the primary regulations, are legally enforceable standards that apply to public water systems. MCLs protect drinking-water quality by limiting the levels of specific contaminants that can adversely affect public health. Secondary Maximum Contaminant Levels (SMCLs) provide guidelines for the control of contaminants that may cause cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as taste, odor, or color) in drinking water. The USEPA recommends SMCLs for public water systems; however, compliance with SMCLs is not mandatory.

The concentrations of most of the analyzed constituents from the 12 well samples were below MCLs and SMCLs. The pH level, however, exceeded the upper SMCL (8.5 units) in samples from 10 of the 12 wells. Another SMCL was exceeded twice; the dissolved-solids SMCL of 500 mg/L was exceeded in the sample from Rough Rock PM5 (636 mg/L) and in the sample from Keams Canyon PM3 (514 mg/L). Samples from three wells had arsenic concentrations that exceeded the MCL of 10 μg/L. Arsenic concentrations were 35 μg/L in the sample from Keams Canyon PM3, 51 μg/L in the sample from Rough Rock PM5, and 18 μg/L in the sample from Second Mesa PM2.

Water from Springs that Discharge from the N Aquifer

In 2002, water samples were collected from four springs in the study area. Burro Spring is on the south side of the study area, the unnamed spring near Dennehotso is on the northeast side, and Moenkopi School Spring and Pasture Canyon Spring are on the west side (**fig. 9**). All the springs discharge water from the unconfined part of the N aquifer.

Water samples from the springs were two water types—the unnamed spring near Dennehotso and Pasture Canyon Spring were a calcium bicarbonate type, and Burro Spring and Moenkopi School Spring were a calcium-sodium bicarbonate type (fig. 12). Samples from the unnamed spring near Dennehotso, Moenkopi School Spring, and Pasture Canyon Spring had low dissolved-solids concentrations of 104 to 191 mg/L (**table 14**). The sample from Burro Spring had a much higher dissolved-solids concentration of 374 mg/L. Concentrations of all the analyzed constituents in samples from the four springs were below current USEPA MCLs and SMCLs (U.S. Environmental Protection Agency, 2002).

From the mid 1980s to 2002, trends are not apparent in the concentrations of dissolved solids, chloride, and sulfate in water samples from Burro Spring, the unnamed spring near Dennehotso, and Pasture Canyon Spring (**table 15**, **fig. 14**). In water samples from Moenkopi School Spring, there appear to be no trends in concentrations of dissolved solids and sulfate and an increasing trend in concentrations of chloride.

Table 13. Specific conductance and concentrations of selected chemical constituents in water from industrial and municipal wells completed in the N aquifer, Black Mesa area, Arizona, 1968–2002

[µS/cm, microsiemens per centimeter at 25°C; °C, degrees Celsius; mg/L, milligrams per liter. Dashes indicate no data]

Year	Specific conductance, field (µS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Forest Lake NTUA 1				
1982	470	---	11	67
1990	375	226	8.2	38
1991	[1]350	183	10	24
1993	693	352	35	88
1994	[1]734	430	56	100
1995	470	274	13	60
1995	1,030	626	86	160
1995	488	316	16	71
1996	684	368	44	79
1997	[1]1,140	714	78	250
1998	489	350	37	71
1999	380	259	16	49
2001	584	398	50	84
2002	452	268	22	50
Hotevilla PM1				
1990	290	192	1.6	5
1991	[1]304	208	0.7	5.4
1993	305	180	1.2	5.5
1994	[1]307	166	1.4	4.8
1995	282	196	1.4	3.7
1996	328	186	1.3	5.3
1997	[1]307	185	1.5	5.2
2001	267	170	1.4	5.2
2002	287	182	1.3	4.8
Kayenta PM2				
1982	360	([2])	4.5	58
1983	375	([2])	5.9	60
1984	[1]370	209	4.2	51
1986	300	181	8.2	30
1988	358	235	3.8	74
1992	383	210	5.6	78
1993	374	232	3.7	78
1994	[1]371	236	4.2	77
1995	371	250	4.2	72
1996	370	238	3.8	76
1997	379	230	3.9	77
1998	349	236	3.7	71
1999	364	236	4.0	72
2001	331	234	5.0	73
2002	363	237	5.1	67

Year	Specific conductance, field (µS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Keams Canyon PM3				
1976	940	---	71	36
1994	907	---	61	26
2002	870	514	63	26
Kitsillie NTUA 2				
1997	[1]524	269	3.6	4.3
1998	379	270	3.8	4.1
1999	454	274	4.0	4.1
2001	409	276	5.0	4.5
2002	439	264	4.5	4.4
Kykotsmovi PM2				
1988	368	212	3.2	8.6
1990	355	255	3.2	9.0
1991	[1]374	203	4.4	7.9
1992	363	212	3.3	8.4
1994	[1]365	212	3.6	8.5
1995	368	224	3.1	6.2
1996	365	224	3.3	8.5
1997	[1]379	222	3.0	8.0
1998	348	223	3.3	7.3
1999	317	221	3.5	7.9
2001	339	230	3.5	8.2
2002	350	215	3.4	7.9
Peabody 4				
1974	200	140	3,8	13
1975	220	144	3.4	13
1976	240	138	2.9	19
1979	220	---	3.9	19
1980	230	139	4.3	13
1986	205	---	4.2	12
1987	194	135	[3]5.0	13
1992	224	125	4.3	12
1993	214	124	[3]3.0	12
1996	214	140	3.8	12
1997	[1]203	139	3.5	12
1999	216	142	4.0	13
2001	181	138	4.0	13
2002	214	133	3.9	13
Peabody 9				
1986	181	---	3.1	4.9
1987	148	102	2.8	4.1

See footnotes at end of table.

Table 13. Specific conductance and concentrations of selected chemical constituents in water from industrial and municipal wells completed in the N aquifer, Black Mesa area, Arizona, 1968–2002—Continued

Year	Specific conductance, field (μS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Peabody 9—Continued				
1990	158	106	1.6	3.0
1991	155	83	2.7	3.1
1993	157	94	1.6	2.9
1994	---	---	1.7	---
1995	154	122	1.6	1.6
1998	109	109	1.7	2.5
2001	88	112	1.8	2.7
2002	152	96	1.7	2.5
Piñon NTUA 1				
1998	460	304	4.6	4.7
2001	473	304	4.9	5.5
2002	512	---	5.0	5.5
Rough Rock PM5				
1983	1,090	([2])	130	110
1984	[1]1,100	613	130	99
1986	1,010	633	140	120
1988	1,120	624	130	[3]110
1991	[1]1,210	574	130	110
1993	1,040	614	130	110
1994	[1]1,070	626	130	110
1995	1,110	648	140	110
1996	1,100	634	130	110
1997	[1]1,060	628	130	110
Rough Rock PM5—Continued				
1998	894	637	130	110
1999	1,050	630	130	110
2001	980	628	120	110
2002	1,120	636	130	110
Second Mesa PM2				
1968	670	---	14	35
1990	590	364	6.5	16
1991	[1]595	292	10	15
1993	630	350	7.5	15
1994	[1]605	342	7.6	15
1995	610	357	7.2	14
1997	[1]646	356	7.1	14
2001	597	352	7.1	15
2002	608	357	7.5	14
Shonto PM2				
1961	290	---	10	16
1973	280	---	7.1	20
1986	302	---	10	14
1988	285	171	13	14
1992	321	186	22	19
1993	324	197	17	16
1996	232	188	15	17
2002	355	215	22	22

[1]Value is different in Black Mesa monitoring reports printed before 2000. The earlier reports showed values determined by laboratory analysis.
[2]Value is different in Black Mesa monitoring reports printed before 2000. The earlier reports showed values determined by the sum of constituents.
[3]Value is different in Black Mesa monitoring reports printed before 2000. The earlier reports applied a different rounding definition.

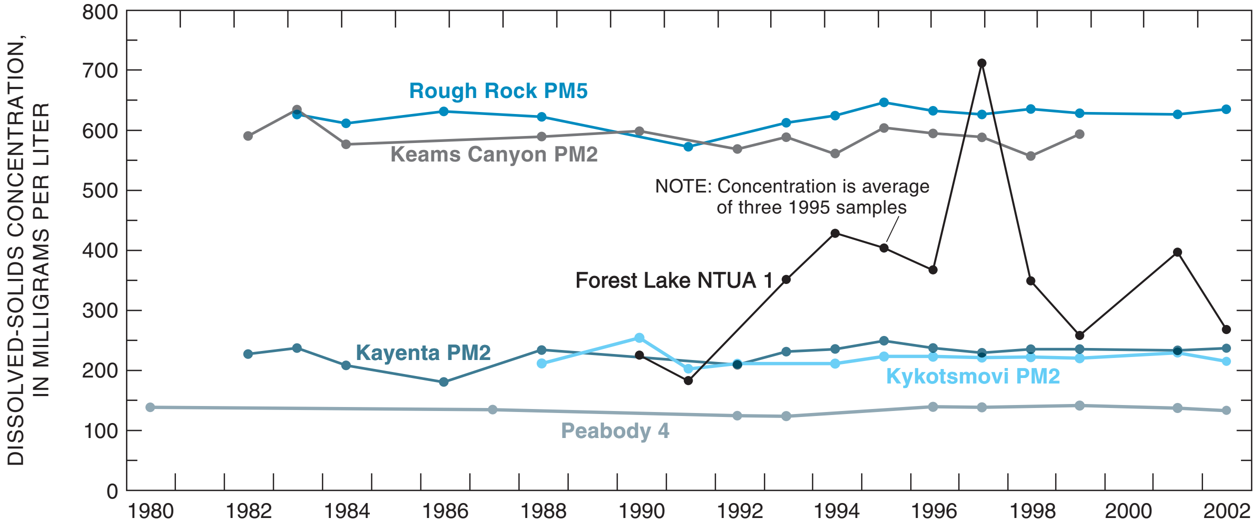

Figure 13. Dissolved-solids concentrations in water from selected wells, Black Mesa area, Arizona, 1980–2002.

Table 14. Physical properties and chemical analyses of water from selected springs that discharge from the N aquifer, Black Mesa area, Arizona, 2002

[°C, degree Celsius; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than. Dashes indicate no data]

Spring name	Bureau of Indian Affairs site number	U.S. Geological Survey identification number	Date of sample	Temperature (°C)	Specific conductance, field (µS/cm)	pH, field (units)
Burro Spring	6M-31	354156110413701	04-03-02	9.9	591	7.3
Unnamed spring near Dennehotso	8A-224	364656109425400	04-03-02	11.6	183	8.3
Moenkopi School Spring	3GS–77–6	360632111131101	06-19-02	18.0	316	7.4
Pasture Canyon Spring	3A-5	361021111115901	04-04-02	16.5	243	7.6

Table 14. Physical properties and chemical analyses of water from selected springs that discharge from the N aquifer, Black Mesa area, Arizona, 2002—Continued

Spring name	Alkalinity, field, dissolved (mg/L as $CaCO_3$)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Hardness (mg/L as $CaCO_3$)	Hardness, non carbonate (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)
Burro Spring	196	<0.05	<0.02	160	---	56
Unnamed spring near Dennehotso	79	1.7	.02	76	---	24
Moenkopi School Spring	97	2.3	<.02	100	---	30
Pasture Canyon Spring	87	4.5	<.02	86	---	28

Spring name	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)
Burro Spring	4.4	60	0.30	31	77	0.3
Unnamed spring near Dennehotso	3.8	4.1	1.0	2.7	7.4	.2
Moenkopi School Spring	6.3	24	1.2	18	23	.2
Pasture Canyon Spring	4.2	11	1.3	5.1	16	.2

Spring name	Silica, dissolved (mg/L as SiO_2)	Arsenic, dissolved (µg/L as As)	Boron, dissolved (µg/L as B)	Iron dissolved (µg/L as Fe)	Dissolved solids, residue at 180°C (mg/L)
Burro Spring	14	1.5	58	<10	374
Unnamed spring near Dennehotso	12	2.5	15	<10	104
Moenkopi School Spring	13	3.0	34	<10	191
Pasture Canyon Spring	9.5	1.9	28	<10	143

Table 15. Specific conductance and concentrations of selected chemical constituents in water from selected springs that discharge from the N aquifer, Black Mesa area, Arizona, 1948–2002

[µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; °C, degrees Celsius. Dashes indicate no data]

Year	Specific conductance (field) (mS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO4)
		Burro Spring		
1989	485	308	22	59
1990	[1]545	347	23	65
1993	595	368	30	85
1994	[1]597	368	26	80
1996	525	324	23	62
1997	[1]511	332	26	75
1998	504	346	25	70
1999	545	346	25	69
2001	480	348	24	68
2002	591	374	31	77
		Unnamed spring near Dennehotso		
1984	195	112	2.8	7.1
1987	178	[2]109	3.4	7.5
1992	178	108	3.6	7.3
1993	184	100	3.2	8
1995	184	124	2.6	5.7
1996	189	112	2.8	8.2
1997	[1]170	98	2.4	6.1
1998	179	116	2.4	5.4
1999	184	110	2.8	6.3
2001	176	116	2.6	6.0
2002	183	104	2.7	7.4
		Moenkopi School Spring		
1952	222	---	6	---
1987	270	161	12	19
1988	270	155	12	19
1991	297	157	14	20
1993	313	204	17	27
1994	305	182	17	23
1995	314	206	18	22
1996	332	196	19	26
1997	[1]305	185	18	24
1998	296	188	18	24
1999	305	192	19	26
2001	313	194	18	26
2002	316	191	18	23
		Pasture Canyon Spring		
1948	[1]227	([2])	5	13
1982	240	---	5.1	18
1986	257	---	5.4	19
1988	232	146	5.3	18
1992	235	168	7.1	17
1993	242	134	5.3	17
1995	235	152	4.8	14
1996	238	130	4.7	15
1997	232	143	5.3	17
1998	232	147	5.1	16
1999	235	142	5.1	14
2001	236	140	5.1	17
2002	243	143	5.1	16

[1]Value is different in Black Mesa monitoring reports before 2000. Earlier reports showed values determined by laboratory analysis.

[2]Value is different in Black Mesa monitoring reports before 2000. Earlier reports showed values determined by the sum of constituents.

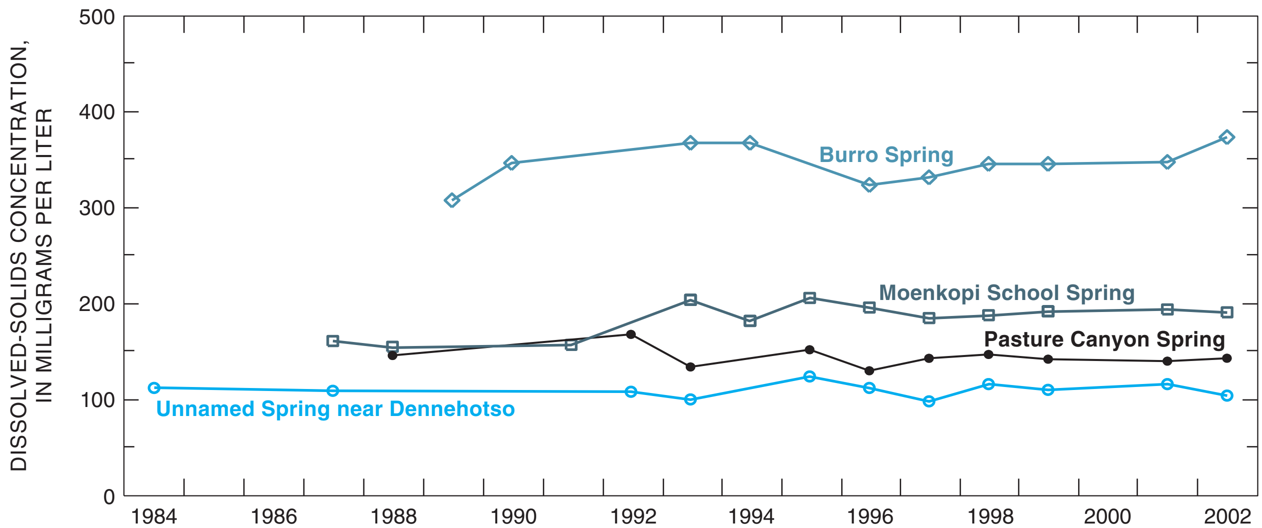

Figure 14. Dissolved-solids concentrations in water from selected springs, Black Mesa area, Arizona, 1984–2002.

SUMMARY

The N aquifer is the major source of water for industrial and municipal users in the Black Mesa area of northeastern Arizona. Availability of water is an important issue in the Black Mesa area because of continued industrial and municipal use, a growing population, and precipitation of about 6 to 14 in/yr.

This report presents results of ground-water, surface-water, and water-chemistry monitoring in the Black Mesa area from January 2001 to June 2002. The monitoring data for 2001–02 are compared with data for 2000–2001 and with historical data from the 1950s to the present.

In 2001, total ground-water withdrawals were 7,680 acre-ft, industrial use was 4,530 acre-ft, and municipal use was 3,150 acre-ft. From 2000 to 2001, total withdrawals decreased by 1 percent, municipal use decreased by 3 percent, and industrial use increased by 1 percent. During the past 10 years, total withdrawals and municipal and industrial use increased at an average rate of about 3 percent per year.

From 2001 to 2002, ground-water levels declined in 17 of 31 wells. The median water-level change for the 31 wells was -0.2 ft, and changes ranged from -22.7 ft to +7.7 ft. In unconfined areas, water levels declined in 5 of 14 wells, and the median change was +0.2 ft. In confined areas, water levels declined in 12 of 17 wells, and the median change was -1.4 ft.

For wells in confined areas, the average annual median water-level change was -1.8 ft, and there is no appreciable trend in the annual water-level changes from 1983 to 2002. For wells in unconfined areas, the average annual median water-level change was +0.2 ft, and there is a break in the trend of annual water-level changes. There is no appreciable trend from 1983 to 1992, and there is a decreasing trend from 1993 to 2001.

From the prestress period (prior to 1965) to 2002, water levels in 32 wells changed by a median of -15.8 ft. Water levels in the 15 wells in the unconfined part of the aquifer had a median change of -1.3 ft, and the changes ranged from -42 ft to +14.6 ft. Water levels in the 17 wells in the confined part of the aquifer had a median change of -31.7 ft, and the changes ranged from -191.5 ft to +15.5 ft.

Discharges were measured annually at four springs in 2001 and 2002. Burro Spring had a 100 percent increase in discharge, the unnamed spring near Dennehotso had an 66-percent decrease, Moenkopi School Spring had a 26-percent decrease, and Pasture Canyon Spring had no change. For about the past

10 years, discharges in the four springs have fluctuated; however, increasing or decreasing trends are not apparent.

Continuous records of surface-water discharge have been collected from 1976 to 2001 at Moenkopi Wash, 1996 to 2001 at Laguna Creek, 1993 to 2001 at Dinnebito Wash, and 1994 to 2001 at Polacca Wash. The annual average discharges at the four streamflow-gaging stations vary considerably during the periods of record. There appears to be a decreasing trend in annual average discharge for Laguna Creek and no trend for the other three gaging stations. Median flows for November, December, January, and February of each water year are used as an index of ground-water discharge to those streams. Since 1995, the median winter flows have decreased for Moenkopi Wash, Dinnebito Wash, and Polacca Wash. Since 1997, there is no consistent trend in the median winter flow for Laguna Creek.

In 2002, water samples were collected from 12 wells and analyzed for selected chemical constituents. Dissolved-solids concentrations ranged from 96 to 636 mg/L, and samples from 8 of the wells had dissolved-solids concentrations less than 300 mg/L. There are no appreciable time trends in the chemistry of water samples from 9 wells with more than 7 years of data. The time periods of these water-chemistry data from wells range from 1961–2002 to 1990–2002.

In 2002, dissolved-solids concentrations in water samples from the unnamed spring near Dennehotso, Pasture Canyon Spring, and Moenkopi School Spring ranged from 104 to 191 mg/L, and dissolved-solid concentration in the water sample from Burro Spring was 374 mg/L. From the mid 1980s to 2002, trends are not apparent in the concentrations of dissolved solids, chloride, and sulfate in water samples from Burro Spring, the unnamed spring near Dennehotso, and Pasture Canyon Spring. In water samples from Moenkopi School Spring, there appear to be no trends in concentrations of dissolved solids and sulfate and an increasing trend in concentrations of chloride.

SELECTED REFERENCES

Boner, F.C., Davis, R.G., and Duet, N.R., 1992, Water-resources data for Arizona, water year 1991: U.S. Geological Survey Water-Data Report AZ–91–1, 411 p.

Boner, F.C., Garrett, W.B., and Konieczki, A.D., 1989, Water-resources data for Arizona, water year 1988: U.S. Geological Survey Water-Data Report AZ–88–1, 391 p.

Boner, F.C., Konieczki, A.D., and Davis, R.G., 1991, Water-resources data for Arizona, water year 1990: U.S. Geological Survey Water-Data Report AZ–90–1, 381 p.

Boner, F.C., Smith, C.F., Garrett, W.B., and Konieczki, A.D., 1990, Water-resources data for Arizona, water year 1989: U.S. Geological Survey Water-Data Report AZ–89–1, 383 p.

Brown, J.G., and Eychaner, J.H., 1988, Simulation of five ground-water withdrawal projections for the Black Mesa area, Navajo and Hopi Indian Reservations, Arizona: U.S. Geological Survey Water-Resources Investigations Report 88—4000, 51 p.

Cooley, M.E., Harshbarger, J.W., Akers, J.P., and Hardt, W.F., 1969, Regional hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: U.S. Geological Survey Professional Paper 521–A, 61 p.

Davis, G.E., Hardt, W.F., Thompson, L.K., and Cooley, M.E., 1963, Records of ground-water supplies, part 1, *of* Geohydrologic data in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: Arizona State Land Department Water- Resources Report 12–A, 159 p.

Dubiel, R.F., 1989, Sedimentology and revised nomenclature for the upper part of the upper Triassic Chinle Formation and the lower Jurassic Wingate Sandstone, northwestern New Mexico and northeastern Arizona, *in* Anderson, O.J., Lucas, S.G., Love, D.W., and Cather, S.M., eds., Southeastern Colorado Plateau: New Mexico Geological Society Fortieth Annual Field Conference, September 28–October 1, 1989, p. 213–223.

Eychaner, J.H., 1983, Geohydrology and effects of water use in the Black Mesa area, Navajo and Hopi Indian Reservations, Arizona: U.S. Geological Survey Water-Supply Paper 2201, 26 p.

GeoTrans, Inc., 1987, A two-dimensional finite-difference flow model simulating the effects of withdrawals to the N aquifer, Black Mesa area, Arizona: Boulder, Colorado, GeoTrans, Inc., report prepared for Peabody Western Coal Company.

Harshbarger, J.W., Lewis, D.D., Skibitzke, H.E., Heckler, W.L., and Kister, L.R., 1966, Arizona water: U.S. Geological Survey Water-Supply Paper 1648, 85 p.

Hart, R.J., and Sottilare, J.P., 1988, Progress report on the ground-water, surface-water, and quality-of-water monitoring program, Black Mesa area, northeastern Arizona—1987–88: U.S. Geological Survey Open-File Report 88—467, 27 p.

____1989, Progress report on the ground-water, surface-water, and quality-of-water monitoring program, Black Mesa area, northeastern Arizona—1988–89: U.S. Geological Survey Open-File Report 89—383, 33 p.

Hill, G.W., 1985, Progress report on Black Mesa monitoring program—1984: U.S. Geological Survey Open-File Report 85—483, 24 p.

Hill, G.W., and Sottilare, J.P., 1987, Progress report on the ground-water, surface-water, and quality-of-water monitoring program, Black Mesa area, northeastern Arizona—1987: U.S. Geological Survey Open-File Report 87—458, 29 p.

Hill, G.W., and Whetten, M.I., 1986, Progress report on Black Mesa monitoring program—1985–86: U.S. Geological Survey Open-File Report 86—414, 23 p.

HSIGeoTrans, Inc., 1993, Investigation of the N- and D-aquifer geochemistry and flow characteristics using major ion and isotopic chemistry, petrography, rock stress analyses, and dendrochronology in the Black Mesa area, Arizona: Boulder, Colorado, HSIGeoTrans, Inc., report prepared for Peobody Coal Company.

HSIGeoTrans, Inc., and Waterstone Environmental Hydrology and Engineering, Inc., 1999, A three-dimensional flow model of the D and N aquifers, Black Mesa Basin, Arizona: Boulder, Colorado, HSIGeoTrans, Inc., and Waterstone Environmental Hydrology and Engineering, Inc., report prepared for Peabody Western Coal Company.

Kister, L.R., and Hatchett, J.L., 1963, Selected chemical analyses of the ground water, part 2 *of* Geohydrologic data in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: Arizona State Land Department Water-Resources Report 12–B, 58 p.

Littin, G.R., 1992, Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1990–91: U.S. Geological Survey Water-Resources Investigations Report 92—4045, 32 p.

____1993, Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1991–92: U.S. Geological Survey Water-Resources Investigations Report 93—4111, 23 p.

Littin, G.R., Baum, B.M., and Truini, Margot, 1999, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona— 1999: U.S. Geological Survey Open-File Report 98—653, 27 p.

Littin, G.R., and Monroe, S.A., 1995a, Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1992–93: U.S. Geological Survey Water- Resources Investigations Report 95—4156, 37 p.

____1995b, Results of ground-water, surface-water, and water-chemistry monitoring, Black Mesa area, northeastern Arizona—1994: U.S. Geological Survey Water-Resources Investigations Report 95—4238, 25 p.

____1996, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1995: U.S. Geological Survey Open-File Report 96—616, 22 p.

____1997, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1996: U.S. Geological Survey Open-File Report 97—566, 27 p.

Lopes, T.J., and Hoffmann, J.P., 1997, Geochemical analyses of ground-water ages, recharge rates, and hydraulic conductivity of the N Aquifer, Black Mesa area, Arizona: U.S. Geological Survey Water-Resources Investigations Report 96—4190, 42 p.

McCormack, H.F., Fisk, G.G., Duet, N.R., Evans, D.W., and Castillo, N.K, 2002, Water-resources data for Arizona, water year 2001: U.S. Geological Survey Water-Data Report AZ–01–1, 399 p.

Smith, C.F., Anning, D.W., Duet, N.R., Fisk, G.G., McCormack, H.F., Pope, G.L., Rigas, P.D., and Wallace, B.L., 1995, Water-resources data for Arizona, water year 1994: U.S. Geological Survey Water-Data Report AZ–94–1, 320 p.

Smith, C.F., Boner, F.C., Davis, R.G., Duet, N.R., and Rigas, P.D., 1993, Water-resources data for Arizona, water year 1992: U.S. Geological Survey Water-Data Report AZ–92–1, 360 p.

Smith, C.F., Rigas, P.D., Ham, L.K., Duet, N.R., and Anning, D.W., 1994, Water-resources data for Arizona, water year 1993: U.S. Geological Survey Water-Data Report AZ–93–1, 360 p.

Smith, C.F., Duet, N.R., Fisk, G.G., McCormack, H.F., Partin, C.K., Pope, G.L., Rigas, P.D., and Tadayon, Saeid, 1996, Water-resources data for Arizona, water year 1995: U.S. Geological Survey Water- Data Report AZ–95–1, 306 p.

Smith, C.F., Duet, N.R., Fisk, G.G., McCormack, H.F., Partin, C.K., Pope, G.L., and Rigas, P.D., 1997, Water-resources data for Arizona, water year 1996: U.S. Geological Survey Water-Data Report AZ–96–1, 328 p.

Sottilare, J.P., 1992, Results of ground-water, surface- water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1989–90: U.S. Geological Survey Water-Resources Investigations Report 92—4008, 38 p.

Tadayon, Saeid, Duet, N.R., Fisk, G.G., McCormack, H.F., Partin, C.K., Pope, G.L., and Rigas, P.D., 1999, Water-resources data for Arizona, water year 1998: U.S. Geological Survey Water-Data Report AZ–98–1, 454 p.

____2000, Water-resources data for Arizona, water year 1999: U.S. Geological Survey Water-Data Report AZ–99–1, 389 p.

____2001, Water-resources data for Arizona, water year 2000: U.S. Geological Survey Water-Data Report AZ–00–1, 390 p.

Tadayon, Saeid, Duet, N.R., Fisk, G.G., McCormack, H.F., Pope, G.L., and Rigas, P.D., 1998, Water-resources data for Arizona, water year 1997: U.S. Geological Survey Water-Data Report AZ–97–1, 416 p.

Thomas, B.E., and Truini, Margot, 2000, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona–1999: U.S. Geological Survey Open-File Report 00—453, 42 p.

Thomas, B.E., 2002, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2000–2001, and performance and sensitivity of the 1988 USGS numerical model of the N aquifer: U.S. Geological Survey Water-Resources Investigations Report 02—4211, 75 p.

Truini, Margot, Baum, B.M., Littin, G.R., and Singoitewa-Honanie, Gayl, 2000, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1998: U.S. Geological Survey Open-File Report 00—66, 37 p.

U.S. Department of Agriculture, Natural Resources Conservation Service, 1999, Arizona Annual Precipitation: Fort Worth, Texas, USDA-NRCS National Cartography & Geospatial Center, scale 1:1,300,000.

U.S. Environmental Protection Agency, 2002, Current drinking water standards, national primary and secondary drinking water regulations: Washington, D.C., U.S. Environmental Protection Agency, accessed April 1, 2002, at URL http://www.epa.gov/safewater/mcl.html.

U.S. Geological Survey, 1963–64a, Surface-water records of Arizona: U.S. Geological Survey report.

____1963–64b, Ground-water records of Arizona: U.S. Geological Survey report.

____1965–74a, Water-resources data for Arizona— Part 1, Surface-water records: U.S. Geological Survey Water-Resources Data Report.

____1965–74b, Water-resources data for Arizona— Part 2, Ground-water records: U.S. Geological Survey Water-Resources Data Report.

____1976–83, Water-resources data for Arizona, water years 1975–81: U.S. Geological Survey Water Resources Data Reports AZ–75–1 to AZ–81–1.

____1978, Progress report on Black Mesa monitoring program—1977: U.S. Geological Survey Open-File Report 78—459, 38 p.

White, N.D., and Garrett, W.B., 1984, Water resources data for Arizona, water year 1982: U.S. Geological Survey Water-Data Report AZ–82–1, 440 p.

____1986, Water resources data for Arizona, water year 1983: U.S. Geological Survey Water-Data Report AZ–83–1, 387 p.

____1987, Water resources data for Arizona, water year 1984: U.S. Geological Survey Water-Data Report AZ–84–1, 381 p.

____1988, Water resources data for Arizona, water year 1985: U.S. Geological Survey Water-Data Report AZ–85–1, 343 p.

Wilson, R.P., and Garrett, W.B., 1988, Water resources data for Arizona, water year 1986: U.S. Geological Survey Water-Data Report AZ–86–1, 341 p.

____1989, Water-resources data for Arizona, water year 1987: U.S. Geological Survey Water-Data Report AZ–87–1, 385 p.

Zhu, Chen., Waddell, R.K., Star, I., and Ostrander, M., 1998, Responses of ground water in the Black Mesa Basin, northeastern Arizona, to paleoclimatic changes during the late Pleistocene and Holocene: Geology, v. 26, no. 2, p. 127–130.

Zhu, Chen., 2000, Estimate of recharge from radiocarbon dating of groundwater and numerical flow and transport modeling: Water Resources Research, v. 36, no. 9, p. 2607–2620.